Mekelle University

Ethiopian Institute of Technology-Mekelle

Faculty of Civil and Environmental Engineering

MSc in Civil Engineering (Environmental and Sustainable Infrastructure Engineering)

Assessing the impact of urban-rural linkage in terms of local construction material flow: the case of Mekelle and surrounding areas

by

Haftay Tsegay Nere

Advisor: Dr. Elfu Amare

Co-advisor: Dr.Yohannes Gebremicheal

January/2026

Mekelle, Ethiopia

Mekelle University

Ethiopian Institute of Technology-Mekelle

Faculty of Civil and Environmental Engineering

Assessing the impact of urban-rural linkage in terms of local construction material flow: the case of Mekelle and surrounding areas

by

Haftay Tsegay Nere

A Master's Thesis Submitted to the Faculty of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science (MSc)

in

Civil Engineering (Environmental and Sustainable Infrastructure Engineering)

Advisor: Dr. Elfu Amare

Co-advisor: Dr.Yohannes G/Micheal

January/2026

Mekelle, Ethiopia

Board of Examiners' Approval

We, the undersigned members of the Board of Examiners for the final open defense of Haftay Tsegay Nere**,** have read and evaluated the thesis entitled "Assessing the impact of urban-rural linkage in terms of local construction material flow: the case of Mekelle and surrounding areas" and assessed the candidate's performance. We hereby certify that the thesis has been accepted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, with specialization in Environmental and Sustainable Infrastructure Engineering (ESIE***).***

Approved by the Board of Examiners

Dr. Elfu Amare		13/02/2026
Advisor	Signature	Date
Dr. Solomon Tsegay		13/02/2026
Internal Examiner	Signature	Date
Dr. Birhane G/Yohannes…		12/02/2026
External Examiner	Signature	Date
Dmtsu Gebremariam		16/02/2026
CPGR	Signature	Date

ACKNOWLEDGEMENT

First and foremost, I give my deepest gratitude to the Almighty God for giving me the life, strength, and perseverance to complete my studies successfully. I would like to extend my sincere appreciation to my main advisor, Dr. Elfu Amare, for his professional guidance, constructive criticism, insightful comments, continuous encouragement, and regular discussions throughout this research, as well as the addition of clarification to the questions raised by internal and external examiners during the paper defense. Without his invaluable support, this study would not have reached its present stage. I am equally grateful to my co-advisor, Dr. Yohannes Gebremicheal, for his thoughtful feedback and consistent guidance during the entire research process. His dedicated support made a significant contribution to the successful completion of this thesis.

Finally, I would like to express my heartfelt thanks to Dr. Birhane G/Yohannes, my external examiner, and Dr. Solomon Tsegay, my internal examiner, for their careful review of the manuscript and their insightful and scholarly comments, which greatly enhanced the scientific quality of this thesis. In addition, I would like to thank the Chair for Postgraduate and Research Dmtsu Gebremariam, for his or her excellent technical guidance, coordination, and leadership, valuable comments, and constructive feedback on my revised thesis. His insightful observations greatly contributed to improving the quality and clarity of this work.

Thus, without their support and endless understanding, this thesis would not have had its present shape. I am thankful to the Environment and Climate Change Protection Agency staff, city municipalities, Woreda Hintalo and Enderta land use and land protection staff, and agricultural experts for their kind and collaborative effort in providing the needed documents for my thesis. I want to thank all manufactured sand and gravel crusher owners and staff across the seven study areas, my informants, for taking the time to meet with me and share information with me during my study.

Furthermore, I have never forgotten the moral and psychological support of my wife, Hiwot, and my children, Roble, Sara, and Nardos.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

BS EN 12620	British/European Standard
EN 15804:2012+A2:2019	Mandatory European Standard for Environmental Product Declarations in Construction
ENVI 5.2	Environment for Visualizing Images
ETM++E5:F27	Enhanced Thematic Mapper
FCC	False Color Composite
FDRE	Federal Democratic Republic of Ethiopia
GHGe	Greenhouse Gas Emissions
GIS	Geographic Information System
Gov't	Government
GPS	Global Positioning System
HHs	Households
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KII	Key Informant Interviews
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LULC	Land Use and Land Cover Change
ML	Maximum Likelihood

MLC	Maximum Likelihood Classification
NIR	Near Infrared
PPE	Personal Protective Equipment
RS	Remote Sensing
SGD	Sustainable Development Goals
SPSS	Software Package for Social Science
STATA	Statistical Software Package
TMs	Thematic Mappers
TOA	Top of Atmosphere
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984
WHO	World Health Organization

ABSTRACT

Rapid urban expansion in Mekelle is driving the extraction of manufactured sand and gravel from surrounding rural areas, leading to increased bareland. This study examined the impacts of urban–rural linkages through construction material flows between Mekelle and nearby rural communities. A mixed quantitative and qualitative research design was applied. Used both primary and secondary data collected through different methods, including questionnaires. Random and purposive sampling methods involved 80 participants. The study was conducted at seven crusher sites in Hareko and Messebo tabias, purposively selected based on post-conflict functionality, proximity to Mekelle, and rural administrative locations. Also, three sand and gravel trading centers in Mekelle were selected based on their reliance on materials sourced from the study areas. The analysis adopted a cradle-to-gate system boundary within the broader cradle-to-grave framework due to data limitations. Results showed that annual production reached 86,680 m^3 of manufactured sand and gravel, of which 15% generated as byproduct. *The material flow chain supported 159 rural and urban residents through wage labor and trading activities. However, socio-environmental impacts were identified, including health risks, carbon emissions (2.23 kg* $C0_2$ */t), and soil degradation. Although mitigation measures were agreed upon, weak regulatory enforcement prevented their full implementation, except for water spraying, which reduced dust emissions by 70% annually (492.41kg/year) but led to raised concerns over unsustainable water extraction. The study highlights policy gaps and recommends stronger regulatory enforcement to ensure sustainable resource management, alongside future research on why environmental policy in Ethiopia has weak in implementation.*

Keywords: Mekelle, Environment, Rural-Urban linkage, Sustainability, Carbon emission

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

Worldwide urban expansion is increasing year after year, intensifying rural-urban linkages, leading to alterations in land use, ecosystems, and reliance on ecosystem services (Desa, 2019; Forster et al., 2021). Local construction material, for instance, sand (Ren et al., 2022), illustrates this dynamic, being one of the most heavily extracted resources worldwide, with annual consumption estimated at 40-50billion metric tons. Previous studies (Mundra et al., 2016), shown that manufactured gravels also comprise 60-75% of the concrete volume, with fine gravel accounting for approximately 35%. Urban expansion is the driving force behind more pressures to natural resources (Tan et al., 2021) which is consuming 70-75% of global natural resources, raises concerns regarding environmental degradation and long-term sustainability. Consequently, the construction sector increasingly relies on manufactured sand produced through rock crushing (Thapa et al., 2020), which provides a consistent alternative to riverine sand extraction.

In Africa, sand and gravel remain essential construction materials with high demand (Ayuk et al., 2020). While gravel and sand mining can provide economic and social benefits, these are often offset by unequal and unjust practices (Hougaard & Vélez-Torres, 2020). Thus, rural–urban linkages associated with sand and gravel extraction supply income and jobs, but activities are frequently linked to unsafe working conditions, health risks, and social problems (Bendixen et al., 2021). This traditional sand mining cannot meet growing demand and contributes to environmental degradation and social conflict over diminishing resources (Hemmler et al., 2024; Torres et al., 2017). Demand for natural sand now exceeds its natural replenishment rate (Sverdrup et al., 2017), emphasizing the need for sustainable alternatives such as manufactured sand to achieve Sustainable Development Goals and inform effective policies (Torres et al., 2021). Without adequate regulation, however, alternative extraction may also produce negative environmental and social outcomes (Vélez-Torres et al., 2024).

Ethiopia's construction sector relies heavily on sand resources but faces challenges such as illegal mining, weak regulatory frameworks, resource depletion, and socio-environmental impacts (Gallagher & Peduzzi, 2019). River sand mining provides rural jobs, but due to weak regulation, it causes environmental degradation and health risks (Nursamsi et al., 2024). Ethiopia's high-purity manufactured sand shows industrial potential, yet adoption is constrained by fragmented production, weak policies, and limited research (Aschale, 2025). Dependence on distant natural sand sources raises

costs and carbon emissions, whereas manufactured sand from sedimentary rock offers a consistent local supply and reduces ecosystem pressure (Mamaru, 2020). Therefore, integrating quarry fines and other by-products enhances resource efficiency and supports Sustainable Development Goals. However, according to the Ethiopian Standard ES C.D3.201 (1990) guideline (MWE, 2018). The fineness modulus of fine gravel should lie between 2.0 and 3.5, ensuring optimal gradation for concrete production (Mathewos & Amare, 2022). These national standards align closely with international benchmarks, emphasizing the importance of controlling particle size distribution and fine content to achieve desirable concrete properties. Similarly, (Tan et al., 2023) demonstrated that M-sand concrete maintains comparable bending strength and durability to river sand concrete when used within the 0.15–4.75 mm range, and it can also influence the mechanical properties of concrete (Nguyen et al., 2022). Furthermore, (Singh et al., 2022) reported that manufactured sand meeting these grading and cleanliness requirements represents a viable and environmentally sustainable alternative to river sand, mitigating the ecological degradation associated with uncontrolled riverbed extraction, but should be used with balanced replacement of river sand with manufactured sand for better workability and strength (Rafi & Aziz, 2022). Furthermore. According to standard construction material specifications such as ASTM C33/C33M (ASTM, 2003), IS 383:2016 (Standard, 2016), and BS EN 12620, manufactured sand, commonly referred to as manufactured sand, is recommended to have a particle size range between 0.15 mm and 4.75 mm when used as fine gravel in concrete.

This study addresses the knowledge gap concerning the environmental and social impacts of sand and gravel extraction, with particular focus on the urban-rural linkage related to the use of these natural resources. The study applies GIS and remote sensing techniques to assess environmental impact by analyzing land use changes from 2005 to 2025. Key questions, such as how bare land has replaced areas formerly used for extraction, farming, and bushland, were addressed. It also identifies methodological and knowledge gaps within the rural–urban linkage framework regarding manufactured sand and gravel consumption. Ultimately, this study is expected to provide valuable insights into rural-urban linkage in the context of sustainable local construction material use, supporting the development of effective resource management strategies for government authorities, practitioners, and researchers at various levels.

1.2 Statement of the problem

The demand for local construction material at the global level (Dinh, 2020) and in the context of Africa (Bendixen et al., 2023) is increasing and exceeds the existing supply, particularly riverine sands. Similarly, in Ethiopia, the rapid urban growth over the past 30 years has led to widespread mining of local construction materials. This growing demand fast-tracked the search for other alternatives, such as manufactured sand and gravel. Despite its widespread adoption and economic benefits in both rural and urban areas, the dual socio-environmental impacts of rural-urban linkage in construction material flow have not yet been studied in Ethiopia in general, including Tigray (Assefa & Gebregziabher, 2020). Existing studies examined economic or environmental dimensions in isolation, exacerbating the knowledge gap with low regulatory enforcement at all levels, particularly in Tigray (Mamo et al., 2024).

Unlike existing studies, this research employed both quantitative and qualitative methods to examine the dual impacts of rural-urban linkages arising from the use of manufactured sand and gravel. The study was conducted within a cradle -to-gate system boundary, excluding a cradle-to-gravel analysis due to data inconsistencies, and followed ISO 14040/44 and EN 15804:2012+A2:2019 standards. Land use and land cover changes over the last 20 years (2005-2025) were analyzed using GIS and remote sensing geospatial techniques, confirming ground-based environmental impacts due to expanded manufactured sand and gravel extraction. Adopting a dual rural perspective informed by social-ecological systems and cause-and-effect frameworks, the study demonstrates how much the construction material flow imposes impacts on socio-environmental sustainability, and how the regulatory framework is responding. These findings provide baseline evidence to support policymakers, practitioners, and researchers in making informed decisions on sustainable material flow use and management that balance environmental protection and economic development. Thus, the paper is expected to shed some light on the national and regional levels on the methodology and knowledge gaps under the framework of the urban-rural linkage in relation to local construction materials use.

1.3 Objective of the study

1.3.1General objective

To evaluate the impacts of urban-rural linkage in terms of local construction material use in the case of Mekelle and the surrounding rural areas.

1.3.2 Specific objective

The specific objectives of the study

1) To quantify the volume of manufactured gravel and sand flow from rural study areas to Mekelle.
2) To evaluate the environmental and social impacts of manufactured sand and gravel.
3) To identify existing mitigation practices at production sites for reducing production impacts.

1.4 Research questions

The study was conducted to answer the following research questions:

1) What is the estimated volume of manufactured sand and gravel flowing from the rural area to Mekelle?
2) What are the social and environmental impacts of manufactured gravel and sand production?
3) Which mitigation practices are implemented at production sites, and how effective are they in reducing production impacts?

1.5 Significance of the study

The study provides insights into the balanced use of local construction materials within rural-urban linkages. It evaluates mitigation practices and their effectiveness in addressing the socio-economic impacts of material flows. The findings offer recommendations to support stakeholders (policy makers, planners, decision makers, researchers) and guide future research on sustained resource extraction and rural-urban development.

1.6 scope of the study

The study used quantitative and qualitative methods within a cradle -to-grave system boundary aligned with ISO 14040/44 and EN 15804 +A2 standards. It focused on urban-rural material flows of manufactured sand and gravel sourced from seven rural quarry sites and three canters in Mekelle city.

The sites were selected based on proximity, post-conflict functionality, and training centers' sourced material flows. Land-use and land-cover changes from 2005 to 2025 were analyzed using GIS and RS techniques. Socio-economic impacts were assessed through key informant interviews (10) and survey data from randomly selected 80 respondents across different age groups.

1.7 Limitations of the study

The study was limited to a cradle-to-grave system boundary due to a lack of consistent data, restricted from conducting a cradle-to-grave material flow. Though laboratory testing and advanced instruments were excluded because of access and cost, participants' direct quote was directly used and reinforced with international-level environmental standards and assumptions. This immediate solution provides insights beyond laboratory analysis and reflects practical-level realities. These benchmarks offered preliminary impact estimates, highlighting areas for future site-specific research.

1.8 Organization of the research paper

The thesis report consists of five interconnected chapters: Chapter one, which presents the introduction, which embeds the background of the study, problem statement, objective, significance of the study, scope, limitation, and definition of key terms. The next chapter, two, holds contextualized literature that establishes a theoretical foundation for the research. In chapter three, the report outlines the materials and methods used in conducting the study, highlighting the research design, data collection, and analysis techniques. Chapter four presents the research results, followed by a discussion interpreting these findings in relation to existing literature. Finally, chapter five summarizes the key findings and provides recommendations for future action.

1.9 Definition of key terms

Manufactured sand: refers to the sand produced through sedimentary crushing, a concept further discussed by (Gondo et al., 2019).

Urban-rural linkage: this focused only on the connection between both areas in terms of local construction material -particularly manufactured sand and gravel, also supported by (Tacoli, 2003).

Land use and land cover change: In this study, the phrase represents the land use types, farmland and bushland, changed over the last 20 years (2005-2025) due to the expansion of manufactured sand and gravel. This concept is also partially discussed by (Langer, 2016), who defines it as manufactured gravel derived from the mechanical crushing of bedrock and naturally occurring unconsolidated stone.

Cradle-to-gate: the system boundary within the concept of cradle to grave, which focuses only on the input -output process of the construction material manufacturing process (WOLF et al., 2010), which excluded the use and end of life of the process.

Life cycle assessment: This is a standardized methodology, as defined in ISO 14040/44, for quantifying the environmental impacts from the input-output process of the local construction material manufacturing process, but excludes the environmental impacts at use and end of life stages for the same reason, from data inconsistency, also presented by (Tang et al., 2022).

Emission factor: An emission factor is an illustrative value that quantifies the amount of a pollutant released into the atmosphere per unit of an activity responsible for its emission (EPA, 2021).

Feed-rate: In gravel and sand crushers, the feed rate is the mass of material introduced into the crusher per unit of time (t/h) (Vasilyeva et al., 2023).

CHAPTER TWO: LITERATURE REVIEW

2.1 Rural–urban linkages in terms of local construction material use

Historically, rural and urban areas were considered distinct, but recent research, for instance (OECD, 2021), emphasizes their deep interconnection through the extraction and movement of construction materials such as sand and gravel. This indicates that rural areas act as the main sources of these materials for nearby towns and cities, whereas urban centers provide the markets, infrastructure, and transport systems that maintain continuous circulation, forming a rural–urban continuum rather than a simple division. This mutuality becomes particularly apparent in rapidly urbanizing regions (Leow, 2020), where growing demand for construction materials links rural extraction sites with expanding urban projects.

These connections have both economic benefits, such as short-term employment opportunities, and income source diversification (Abate, 2016), as well as socio-environmental problems such as decline of soil fertility, health problems, land degradation, etc.,(Achalu et al., 2023; Nemati & Tahmoorian, 2020). For instance, (Hackney et al., 2021) found that satellite imagery of sand extraction between 2016 and 2020 exceeded the natural sediment supply, causing riverbeds to lower at a median rate of −0.26 meters per year, and declines in soil fertility indicators compared with unmined fields (Hemmler et al., 2024); for example, average reductions of 0.6 g kg^{-1} nitrogen, 12.7 mg kg^{-1} phosphorus, 77 mg kg^{-1} potassium, and 6.3 g kg^{-1} organic carbon were recorded. . Land-use competition is another emerging concern (Teku, 2025) from the connection, as the expansion of extraction activities increasingly overlaps with farmland, settlements, and conservation zones, generating conflicts between rural communities, private investors, and informal operators. Such conflicts highlight governance weaknesses and unclear land tenure systems, which undermine equitable rural–urban linkages.

2.2 Local construction material flows and their implications

2.2.1 Material flow: economic and environmental significance

Economic importance: The majority of the Ethiopian rural population's livelihood is largely dependent on rainfed agriculture (Teferi et al., 2025), which is more vulnerable to natural and manmade vulnerabilities. This led many households to depend on the extraction of natural resources, such as river sand and stone extraction, in addition to the on-farm activities like honey bee production (Sime & Aune, 2019), to diversify their livelihood income sources and to build their resilience capacity to risks. Thus, the extraction of locally available construction material like riverine sand, as well as manufactured sand and gravel (Gudissa et al., 2021), as a sustained alternative to riverine sand (Shewatatek et al., 2022), generates employment and income and supports alternative livelihoods, strengthens urban-rural linkage, while addressing local construction material flow in the cities and towns. For example, manufactured and riverine sand extraction reduces unemployment and provides a steady income (Adanu et al., 2025; Vural et al., 2025; Worku, 2017), contributing positively to local livelihoods (Abdulazeez, 2023). Thus, the material flow links rural livelihoods to urban economic demand, as sand and gravel are essential for housing and infrastructure (Global-T., 2025). These economic significances are also reinforced by temporary transport markets (Yao, 2022), machinery rentals, and local trade in locally manufactured construction materials. In this case, recent studies (Kamble et al., 2019) reported that manufactured sand is generally more cost-effective than river sand, especially when river sand is scarce or expensive to transport, although its finer texture increases cement use.

The key problem frequently asked in the area of these construction material mining is related to the low female engagement in sand and gravel production due to perceptions of physical difficulty and gender norms (TheGlobalEconomy.com, 2024). Besides, the participation declines with age-related patterns, with most quarry workers aged 30–40, and participation declines sharply after 50 due to physical demands (Kitole et al., 2025).

Socio-environmental consequences: Acknowledging the economic benefits from natural construction material extraction also leads to environmental and social impacts. The rapid urbanization has increased demand for sand and gravel, often exceeding regulatory capacity (Beiser, 2019), raising the risk of unsustainable extraction. For instance, unmanaged quarrying, which lacks the implementation of proper mitigation measures, resulted in degraded cropland and grazing areas (Balcha & Oyda, 2021), reduced yields up to 60% (Kresojević et al., 2023; Pal & Mandal, 2021),

lowered soil fertility, altered soil structure (Amour & Haji, 2024; Leake et al., 2020), damaged vegetation, and depleted of native tree species (Wondimu, 2021). Mining dust and quarrying impair photosynthesis, hinder plant growth, and reduce crop and vegetation productivity, contributing to ecosystem deterioration (Lee et al., 2024; Sultan et al., 2025; Zhao et al., 2025).

Communities affected by quarrying often experience inadequate land compensation (Gemeda et al., 2023), delayed payments, and unmet employment promises, leading to grievances. Declining raw material quality increases waste and environmental stress (Tegegne, 2022), while improper dumping exacerbates land degradation and triggers conflicts over farmland loss and livelihood insecurity, and is more pronounced in conflict-affected areas (Elnourani et al., 2024; Gashaw & Aklilu, 2020; Meaux et al., 2022). Vegetation removal and bare surfaces from quarrying contribute to local heat-island effects, as exposed soil and rock absorb and radiate more heat than vegetated areas (Swift et al., 2023; Vural et al., 2025)and are a key contributor to the energy footprint and Co2 emissions, combined with the diesel-powered crushers. For instance, in semi-arid regions of Ethiopia, sand and gravel extraction can raise daytime temperatures by 1–2 °C and maintain higher nighttime temperatures, loss of scenic landscapes, making natural areas less visually appealing, and dramatically alter landscape appearance and visual character (Dentoni et al., 2020; Gebru et al., 2025; Muriki et al., 2024; Yusuf, 2014).

Moreover, a study in Ethiopia (Saleem & Ayalew, 2025) indicated that manufactured sand and gravel operations produce substantial air pollution, dust emissions, and noise. As per the different studies in Ethiopia (Belay et al., 2025; Bikeko & E, 2024; Gitima et al., 2025) shown that, land use land cover change due to manufacturing sand and gravel expansion led to the reduction of carbon stocks and sequestration, alters hydrological cycles and microclimate, increases land surface temperature and reduces moisture, disrupts rainfall and hydrology, and affects local climate through evapotranspiration. Diesel-powered crushers not only contributes land degradation but also contribute hundreds of millions of tonnes of CO_2 emissions annually, underscoring that combustion sources dominate industrial emissions without decarbonization or fuel shifts (Peppas et al., 2024). Ethiopia's electricity grid is predominantly low-carbon (LCP, 2023), supplied primarily by hydropower, which keeps electricity-related emissions very low compared with fossil-fuel-dominated grids in many other countries. Mining-induced habitat loss has disrupted nearly 70% of key freshwater channels, threatening biodiversity and aquatic ecosystems (Han et al., 2023). The environmental burdens, including biodiversity loss, hydrological changes, and landscape degradation, are primarily borne by rural communities, while urban centers capture most economic gains (Kafu-Quvane & Mlaba, 2024).

Therefore, the rural-urban linkage in terms of these two construction material flows provides employment, links rural and urban economies, and supports infrastructure development. However, this untapped potential, especially in the case of Tigray, and Ethiopia in general, often relies on unsafe labor, particularly among youth, and competes with agriculture for land, undermining food security and deepening rural poverty (Yosef & Shifera, 2023) particularly from weak regulatory enforcement, which led to the externality of socio-environmental issues (Akanwa et al., 2025). This highlights the need for sustainable and equitable management of the material flows (Poonia et al., 2024).

2.2.2 Health and social consequences related issues

Different studies in Africa (Ahadzi et al., 2020; Farnham et al., 2020), have shown that residents close to large-scale mining areas reported elevated cases of respiratory disorders and hypertension, frequently experience coughing, eye irritation, chest pain, and sleep disruption due to dust emissions and blasting activities, which were linked to high dust concentrations and insufficient protective measures.

In Ethiopia, workers engaged in manufactured sand and gravel production are highly exposed to hazardous conditions with excessive dust exposure, leading to a high incidence of respiratory diseases, especially in settings where safety training and protective equipment are limited (Ashuro et al., 2023; Islam et al., 2023). While not strictly clinical, a survey in Western Ethiopia documents air pollution (dust) and health-related impacts, including asthma, chronic bronchitis, coughs/colds, and stress, linked to crushers for local construction and mining (Endalew et al., 2019; Upadhyaya, 2021). This indicates that, despite supporting rural livelihoods in Ethiopia, such activities continue to pose respiratory threats to humans, livestock, and pollinators (Asgedom, 2023). Exposure to dust contributes to respiratory diseases not only in humans but also in livestock, with cattle being particularly vulnerable to bronchitis and pneumonia, while pollinators such as bees experience impaired respiration and reduced foraging activity (Ricigliano et al., 2025). Dust accumulation on vegetation lowers forage quality and availability, negatively affecting livestock health and productivity (Gebru et al., 2016) and increasing the likelihood of animal injuries (Rehman et al., 2021). Studies in Ethiopia (Worku et al., 2022) that focused on examining honey bee colony losses identified environmental stressors, including dust pollution, as major factors contributing to colony decline. High honeybee colony losses in Tigray are linked to habitat degradation, dust, and noise (Hailu et al., 2024). This is also connected with the fact that air pollution reduces floral diversity, adversely affecting honeybee foraging and colony health (Bareke & Addi, 2020). Thus, the decline in pollinators reduces

crop yields and seed germination, emphasizing ecological and agricultural consequences (Bareke et al., 2025).

These findings highlight the need for improved occupational safety practices, including proper training and access to PPE, as well as integrated land restoration initiatives and greening projects (Abera et al., 2020; Susca et al., 2011) to keep the amenity of the environment, and further to reduce health risks associated with dust pollution from sand and gravel extraction. The evidence also rectifies the context, relevance, and importance of this research paper for sustainable economic and socio-environmental development in Tigray and Ethiopia in general.

2.2.3 Policy framework for local construction materials mining

Today, the extraction of natural resources for economic growth at the cost of the environment has led to depletion of the resources; therefore, the need for more sustainable construction material governance is becoming a global concern (Sutton et al., 2016). However, the response remains weak (Nelson et al., 2023), particularly in developing countries, where the policy framework suffers from weak enforcement, and short-term planning dominates. For instance, a review of the implementation of SDG (Baffoe et al., 2021)shows that rural-urban material flows are frequently overlooked within the national sustainability framework.

Ethiopia, has environmental focused key federal laws, proclamations, and supporting documents under the umbrella of the national environmental policy (Authority & ABABA, 1997), which aligned with the national constitution (Steen, 1936; Vestal, 1996). The environmental laws, procurement and supporting document includes:

- The environmental and Social Impact Assessment Proclamation No.1371/2025, which integrates socio-environmental considerations into development projects. replaces order law; integrates socio-environmental considerations for development projects (Ababa, 2025). This supported with the Environmental Pollution Control Proclamation No. 300/2002 , which regulates pollution prevention, control, and environmental standards , including waste management (Negarit, 2002).
- The Public Health Proclamation No.200/2000, and Labour Proclamation No.377/2003, with the 2008 Occupational Safety and Health Directive providing practical guidelines on exposure control and risk management (Seblework, 2006).

- The Environmental and Air Quality Standards set limits for pollutants like particulate matter, guiding Proclamation No. 300/2002 standards.
- The UNDP-EPA Legal Environmental Assessment (2025) provides Ethiopia's legal framework on air pollution and health, including recommendations for air quality laws and regulations.

These policies and supporting documents encourage the adoption of sustainable operational practices and meaningful community engagement (EEPA, 2025; Saleem & Ayalew, 2025).

However, the enforcement of these environmental and health safeguarding policies and guidelines remains weak (Misrak et al., 2023). This limited enforcement led to laws and frameworks not being effectively translated into measurable action on the ground (Mitike et al., 2016). This institutional weakness is further reflected in Ethiopia's national assessment of greenhouse gas (GHG) mitigation performance, which identifies limited implementation of mitigation measures beyond natural resource management and a lack of practical policy grounding (FEPA, 2022). The quarry site management is rarely integrated into local land-use planning, creating governance gaps where customary land tenure systems intersect poorly with formal regulations (Kassa et al., 2017). Besides, there is also inadequate coordination among government stakeholders, as a result of sharing responsibilities across ministries without effective joint planning for shared actions. For instance, limited capacity for occupational health enforcement, widespread use of fuels, continues to drive air pollution, as 90-95% of households use biomass for cooking/heating (Redi, 2024). This, integrated with the under-sourced health infrastructures, led to low public and policymaker awareness and stakeholder engagement (Andualem et al., 2025).

2.2.4 Current mitigation practices in study areas

The rural and urban areas are the two faces of a coin in different dimensions, including the nexus regarding the use of local construction materials. So, the proper extraction of the rural construction materials is very critical for sustained rural-urban development while maintaining the environment. Because the raw material for economic development is always sourced from the environment, mainly from rural areas. However, due to weak regulatory enforcement, externality was observed as a persistent problem. For instance, dust suppression through water spraying during manufactured sand and gravel is commonly poorly managed, resulting in excessive water use that strains local water resources and exacerbates shortages for domestic and agricultural purposes in rural communities (Sairanen & Rinne, 2019). While water spraying is widely recognized as an effective dust control

measure, its unregulated and water-intensive application can lead to additional sustainability challenges, especially in water-scarce rural areas in the country in general. In Ethiopia and other rapidly urbanizing regions, declining natural sand reserves have increased costs and informal extraction, while the growing reliance on manufactured sand and gravel has generated new ecological and social risks where regulation and water-efficient technologies are lacking. The weak policy implementation exposed the sites to land degradation. As indicated in the slope range report (FAO, 2019), and more detailed in Ethiopia (Getachew & Meten, 2021); different areas with sloping nature can be exposed to land degradation if their resources are extracted with no mitigation measures. This situation calls for integrated conservation responses, particularly from the investors, with close monitoring and follow-up from the relevant government stakeholders.

These previous and recent study results evidenced that sustainable construction material use and management strategies are becoming the next unanswered questions in the sector. Addressing these challenges requires integrated governance approaches that include monitoring material flows, actively engaging communities, and enforcing extraction standards more rigorously. Enhancing governance, protecting environmental resources, and encouraging local participation are therefore essential to achieve sustainable socio-economic benefits without compromising ecological integrity. Therefore, this study provides a baseline and recommended practical points that support policy makers and planners, which require complementing regulatory enforcement to reduce environmental risks while supporting resilient rural development.

2.2.5 Study focus and methodological additions

This study, which employed a quantitative and qualitative research design, was conducted under the input -output system boundary (cradle-to-grave). It examined the socio-economic impact of urban-rural linkage on the use of two locally available construction materials, manufactured sand and gravel. The ground-level observed environmental problems from the material extraction are supported by the GIS and RS geospatial technique land use land cover map outcome over the last two decades (2005-2025). The study, which has not yet conducted by previous or recent studies, also embedded the socio-ecological system under the equation of cause-effect causality, which aligns with the EN 15804+A2 standards. The estimation of the total volume of material flow enabled us to understand the mass balances, making it easier to understand and work in depth on the next variables.

The study used purposive and random sampling methods to gather data from 80 respondents, including farmers, experts, and government officials, to capture their perceptions, practices, and perspectives on potential sustainability strategies (Habtie et al., 2024; Tesfaye et al., 2021). Both open- and closed-ended questionnaires were administered, and the quantitative data were analyzed using statistical software such as STATA and Excel to generate tables and graphs. Direct quotes from participants were included to complement and reinforce the quantitative findings. In addition, relevant formulas were applied to calculate material flow volumes and their environmental effects, as detailed in the annex of this report. Based on these different research findings, the study proposed practical sustainability measures aimed at guiding policymakers, as well as urban and rural planners, by providing actionable recommendations for equitable resource management and environmentally responsible material sourcing.

2.2.6 Conceptual framework

Taking rapid urban expansion as the point of departure, this conceptual framework examines the increasing pressure on the extraction of two key local construction materials. It illustrates the relationships among the different variables aligned with specific objectives of the study. Sites were selected based on criteria such as post conflict crushers functionality and other relevant factors. The total volume of local construction material flow (SO1) was estimated using simple arithmetic formulas to better understand the mass balance, which informed subsequent variables under SO2 and SO3.

The interaction between environmental systems and human activities within the rural-urban linkage framework generated both spatial and economic linkages, encompassing socio-environmental impacts. The term “impact” refers to both positive (useful) and negative (harmful) effects of material flow. Short-term job creation and sustained supply of construction materials in rural and urban areas were identified as key positive impacts.

Conversely, negative impacts included a reduction in farmland size, destruction of livelihood activities, exposure to health risks from dust and open defecation, and cultural impacts associated with landscape change. These were categorized as direct (primary) and indirect (secondary) impacts. Primary environmental impacts included soil and hydrological degradation, vegetation and biodiversity loss, and visual and landscape degradation. Secondary environmental impacts comprised air and noise pollution, as well as climate and microclimate changes. Direct field observation was systematically supported by land use and land cover (LULC) map analyses using GIS and remote sensing (RS) techniques. Changes over the past 20 years (2005-2025), particularly the expansion of

manufactured sand and gravel extraction into farmland and bushland, were confirmed through special analysis and linked to environmental impacts from the change. Additional geospatial tools, including slope mapping of the study areas, further demonstrated how extraction activities intensified environmental degradation, especially in ecologically sensitive and previously conserved hillside areas.

The conceptual framework also presented the policy framework practices under SO3 to address the socio-environmental negative impacts from the material flow. Under this framework, the prime mitigation practice identified to address the environmental impacts was spraying water. The social negative impacts were addressed through payment for leased lands, health and welfare support, infrastructure development, and fertilizer support for the farmers affected in their farms with due care. Methodologies and assumptions employed in the study are also presented under Annex-II-e.

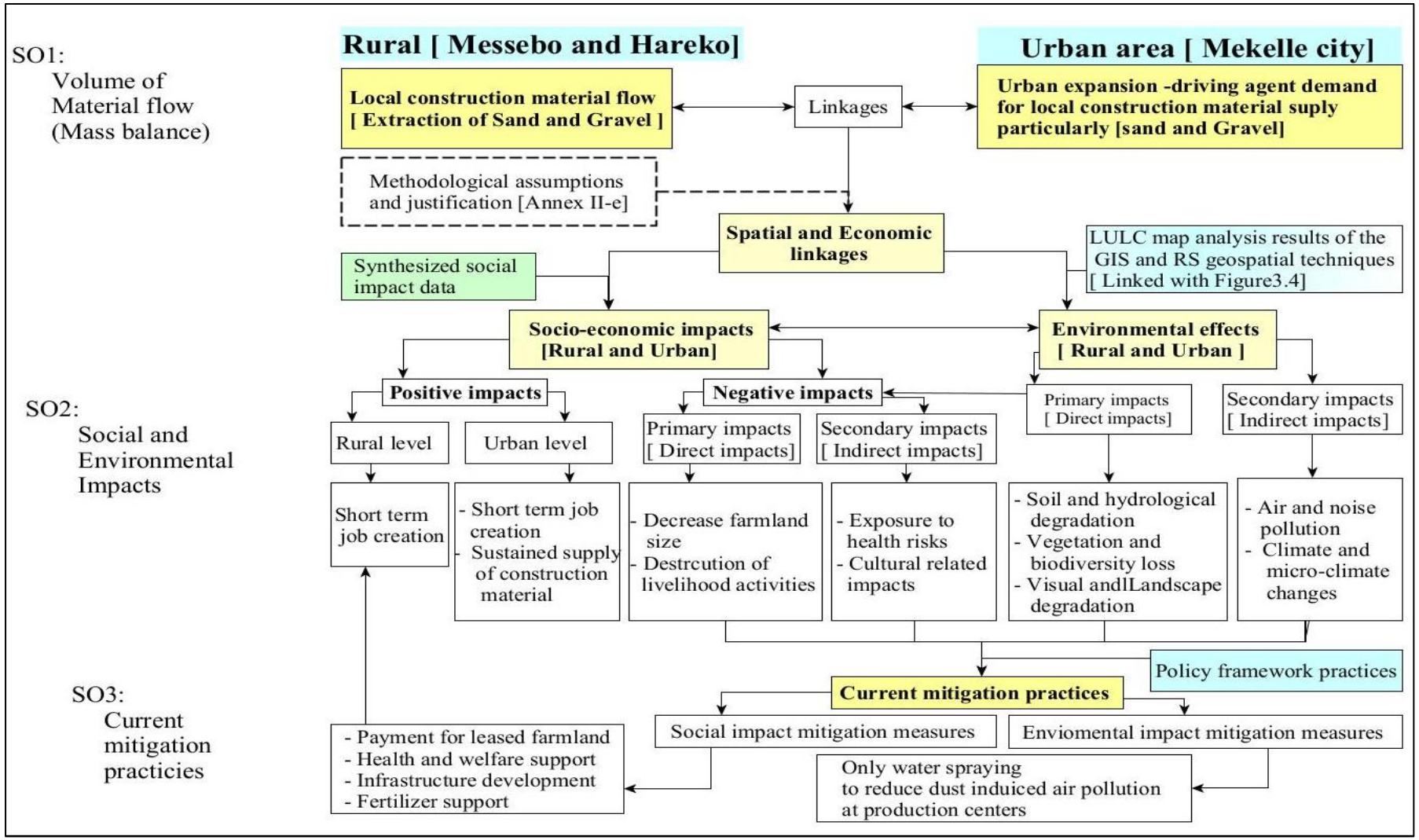


Figure 2. 1: Conceptual framework of the study

Source: Own conceptual understanding of the researcher (2025)

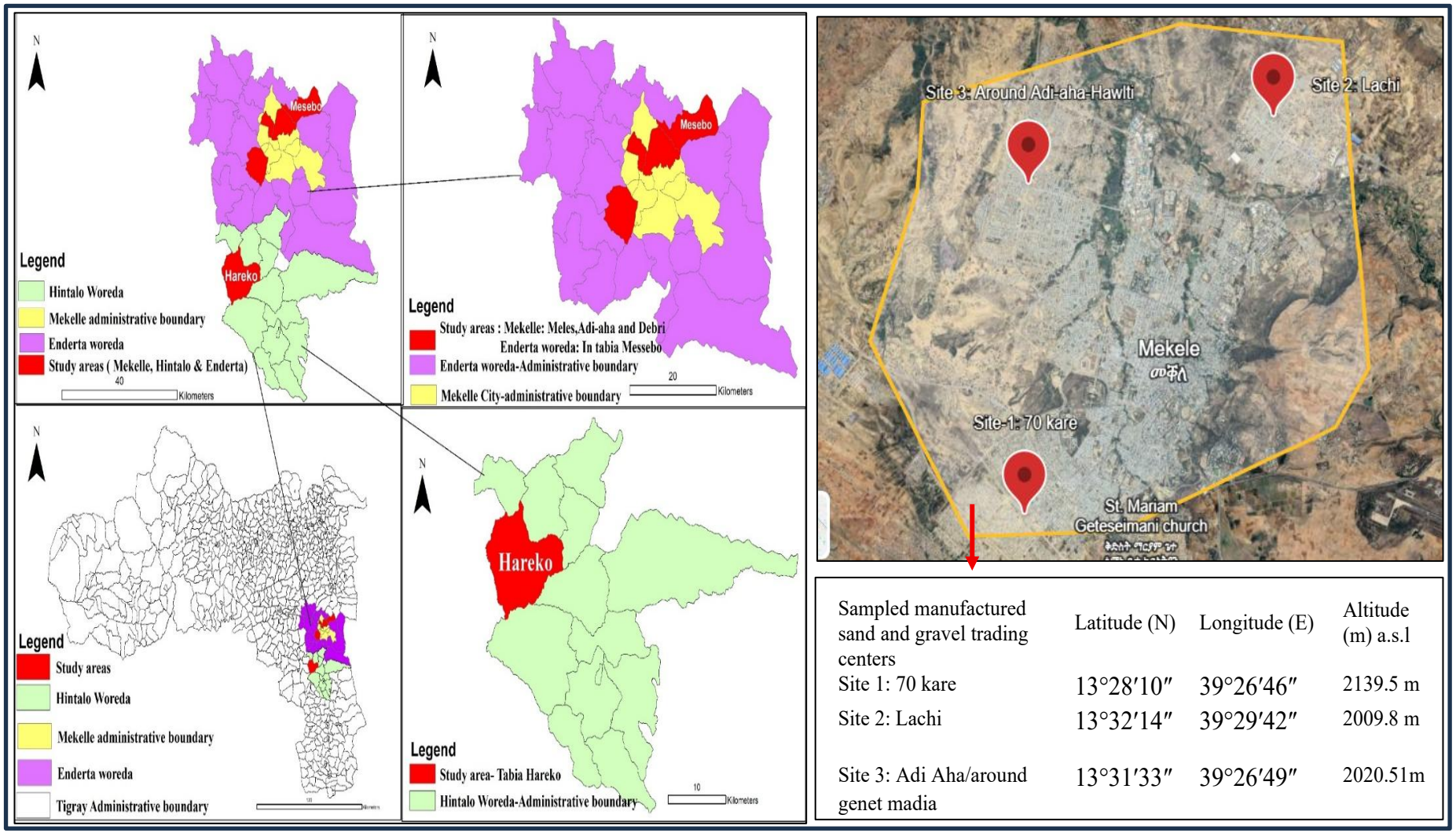
CHAPTER THREE: RESEARCH DESIGN AND METHODOLOGY

3.1 Description of the study area

The study was conducted in Mekelle and its surrounding rural areas. Mekelle city is located in Tigray, northern Ethiopia, between latitudes 13°24′1″ and 13°29′15″ N and longitudes 39°23′15″ and 39°30′8″ E. Administratively, the city comprises seven sub-cities: Quiha, Adi Haqi, Kedamay Weyane, Hadnet, Hawelti, Ayder, and Semien.

The study examined manufactured sand and gravel, sourced from two sites near Mekelle city in the rural districts of Enderta and Hintalo, in the southeastern zone of Tigray. Seven crusher sites were included in the study: four in Hareko tabia, which produce manufactured sand from sedimentary rock crushing using electric and fuel-powered crushers, ensuring a year-round supply, and three in Messebo tabia, which produce gravel from limestone. These sites were selected for their functionality and proximity to the city compared to others. The sites from both rural areas show outstanding economic and environmental impacts, prompting the researcher to assess rural-urban linkages and the effects of local material flows in a developing context.

The study also included three sites for manufactured sand and gravel trading centers in three sub-cities of Mekelle: Semn sub-city (Tabia Meles-Lachi: 13°32′14″N, 39°29′42″ E), Hadnet sub-city (Debri-70 kare:13°28′10″N, 39°26′46″E), and Ayder sub-city (13°31′33″ N, 39°26′49″ E). These trading centers were selected to track urban-rural economic linkages arising from material flows, as they exclusively purchased the two local construction materials from the study areas.



Sampled manufactured sand and gravel trading centers	Latitude (N)	Longitude (E)	Altitude (m) a.s.l
Site 1: 70 kare	13°28′10″	39°26′46″	2139.5 m
Site 2: Lachi	13°32′14″	39°29′42″	2009.8 m
Site 3: Adi Aha/around genet madia	13°31′33″	39°26′49″	2020.51m

Figure 3. 1: Locational map of study areas

3.2 Research design

This study applied a mixed-methods design to evaluate the economic and environmental impacts of sand and gravel production within the local economy of Mekelle City. The design was guided by methodological assumptions, including the representativeness of selected sites and respondents, the reliability and applicability of primary and secondary data, consistency of operational conditions, completeness of material and energy flows, and clearly defined system boundaries. These assumptions ensured transparency regarding the study's scope, limitations, and interpretation of results.

Quantitative data were collected through structured surveys of 80 purposively selected participants, while qualitative insights were obtained from key informant interviews with quarry managers, local officials, and subject-matter experts. Purposive sampling ensured that participants with direct operational knowledge of sand and gravel production were included**.**

3.3 Methodology and assumptions

3.3.1 Sampling method and sample size determination

A purposive sampling method was used to select both quarry sites and respondents to ensure relevance and accuracy. Four sand production sites (Hareko) and three gravel production sites (Tabia Messebo) were chosen based on three criteria: *1) Location*: focusing on rural areas to evaluate urban–rural linkages in sand and gravel use; 2*) Proximity to Mekelle city*: to assess socio-economic interactions; *3) Functionality*: emphasizing active production sites compared with sites that had supplied the city after the conflict. From a total population of 25,924, the sampling frame was narrowed to 100 eligible households exposed to manufactured sand and gravel production activities. Using Yamane's formula (Yamane, 1973), with a 95% confidence level and 5% margin of error, the final sample size was determined as 80 respondents (Simarjeet, 2017).

$$n = \frac{N}{[1+N(e^2)]} \quad \text{.....eqn (1)}$$

$$n = \frac{100}{[1 + 100(0.05^2)]} \cong 80$$

Where;

- n sample size
- e error tolerance (=0.05)
- N population

Assumptions and justifications: Respondents included both genders and provided insights into employment, income, and the environmental effects of production. The representativeness of the study was grounded in data collected from 80 respondents across multiple quarry sites, which were assumed to reflect typical sand and gravel production practices within the study area. The assumption was also aligned with the study (Kirkendall & White, 2018), which showed that calculated sample sizes are enough for basic statistical analysis.

Table 3. 1: Sampled respondents per site

Administrative location of study areas				Total population size			Sample size		
Zone	Woreda /sub-cities	Site names	Administrated under	Male	Female	Total	Male	Female	Total
South eastern	Hintalo	Hareko (4 sites)	Rural areas	35	15	50	30	15	45
	Enderta	Messebo (3 sites)		25	4	29	18	4	22
Mekelle	Semen	Meles	Mekelle sub-cities	7	1	8	5	1	6
	Hadnet	Debri		6	2	8	2	2	4
	Ayder	Adi-aha		3	2	5	1	2	3
Total				76	24	100	56	24	80

3.3.2 Data collection and type of data used

Both primary and secondary data were collected using the following tools utilized. The primary data obtained through questionnaires, interviews, field observations, on-site operational logs, and direct measurements are considered reliable indicators of actual quarry operations. In the case of site-specific measurements incomplete or unavailable, secondary data collected from reviewed internationally recognized modules, as well as reports, were practiced and assumed to apply to the local operational and climatic context.

3.3.2.1 Questionnaires

Structured questionnaires were used to collect socio-economic and unforeseeable environmental data from the 80 sampled respondents. This combination of quantitative and more calculated qualitative

data ensured a holistic understanding of local economic dynamics and environmental problems driven by extraction activities.

3.3.2.2 Field observations

Field observations and discussions with relevant stakeholders were conducted throughout the research process, from topic initiation and proposal development to questionnaire design and data collection. These activities refined the research design and provided contextual understanding of site-specific practices. Observations indicated that all production sites experienced significant land cover changes and varying levels of dust suspension, corroborating GIS analyses and interview findings. Visual documentation and systematic note-taking ensured consistency and objectivity across sites, while assessments of mitigation measures, such as dust control and land restoration practices, provided additional qualitative insight.

3.3.2.3 Quantitative measurements

On-site measurements were conducted to quantify resource consumption and waste generation for a life-cycle inventory. These included diesel and electricity use for crushers, loaders, trucks, and excavators; freshwater use for dust suppression; and generation of quarry fines and other by-products. Field-level verification was conducted in both production and consumption areas, including GPS tracking, water tap measurements, and cross-checking against secondary office data to validate primary observations.

3.3.2.4 Key informant interviews

These interviews generated qualitative insights into daily operations, energy use, dust control, and the challenges of enforcing environmental regulations in rural settings. Managers provided operational data to complete field measurements, while government officials contextualized policy gaps and rural-urban planning dynamics. These perspectives were critical in interpreting trends observed in both quantitative survey data using the LCI method and GIS and RS geospatial systems.

Figure 3. 2: Sample key informant (site manager) interview from Hareko Tabia study area

3.3.5 Remote sensing techniques

3.3.5.1 Global Positioning System (GPS)

To assist with ground-truthing, the researcher collected 13 ground control points (training sites) using GPS devices. These points served as representative samples for the five identified land cover types and were used during the georeferencing of the imager dataset. Finally, the georeferenced sites were compiled to create a key that assigns numerical values to the land use types based on their spectral

3.3.5.2 Data acquisition

Table 3. 2: Characteristics of Landsat Imagery

Sensors	Path and row	Acquisition dates	Resolution
Landsat 7 ETM+	169/051	03/01/2005	30mx30m
L8 OLI \TIRS	169/051	25/01/2015	30mx30m
L8 OLI \TIRS	169/051	13/01/2025	30mx30m

The baseline LULC map was developed using up-to-date satellite imagery, with careful selection of data sources, high resolution, and temporal coverage to ensure accuracy. Landsat thematic mapper and enhanced thematic mapper (ETM+) images from 2005,2015, and 2025 were utilized. The images were downloaded as TIF files from the USGS website (Wulder et al., 2019), extracted from zipped formats, filtered to less than 8% cloud cover, and all had a 30-meter resolution with path and row scenes 169/051.

3.3.4 The system boundary and exclusions

3.3.4.1 Life Cycle Inventory (LCI)

The system boundary was clearly defined as cradle-to-gate -module A1-A3 (Üçtuğ et al., 2025). All material and energy flows crossing the defined system boundary were assumed to have been fully recorded and documented, supporting inventory completeness within the selected scope. Accordingly, all relevant inputs and outputs of the product system were systematically collected and quantified. As detailed in Figure 3.3, the measured parameters across the input-output process consist of extraction, loading, hauling, crushing, screening, and storage. While the key inputs include 1) diesel fuel consumption per annum for each vehicle: loaders, trucks, excavators, including the number and type of diesel-powered crushers, 2) electricity consumption for crushers, screens, and conveyors, and 3)

amount of freshwater consumption per annum per site, aiming for dust suppression. As required in LCI development, these parameters were recorded to ensure that all material and energy flows crossing the system boundary were quantified with transparency and completeness, aiming to avoid bias related to data inconsistency.

- ***Energy consumption*:** The energy and material flow data following the input-output module were collected from the core of the study areas. The number and type of vehicles and crushers across the study area were registered, including the total amount of diesel consumed per year. To elaborate on this, diesel fuel consumption (L/year) was collected from on-site operational logs of each type of vehicle: loaders, trucks, excavators, including the types and number of diesel-powered crushers. Similarly, the electricity consumption (kWh/year) per study area was based on meter readings and annual bills for crushers, screens, and conveyors.
- ***System boundary:*** The system boundary was defined from raw material extraction (quarrying) to the output of crushed and screened manufactured sand and gravel ready for transport. In this case, the primary data were obtained from on-site measurements and operational logs, while secondary data, including emission factors, were derived from IPCC guidelines (Eggleston et al., 2006). Other modules of the EN 15804 +A2 that include transport to the site and installation (A4–A5), use phase (B1–B7), end-of-life (C1–C4), and benefits beyond the system boundary (D1) were excluded due to inconsistent and incomplete data availability, further helping to avoid bias related to data validity.

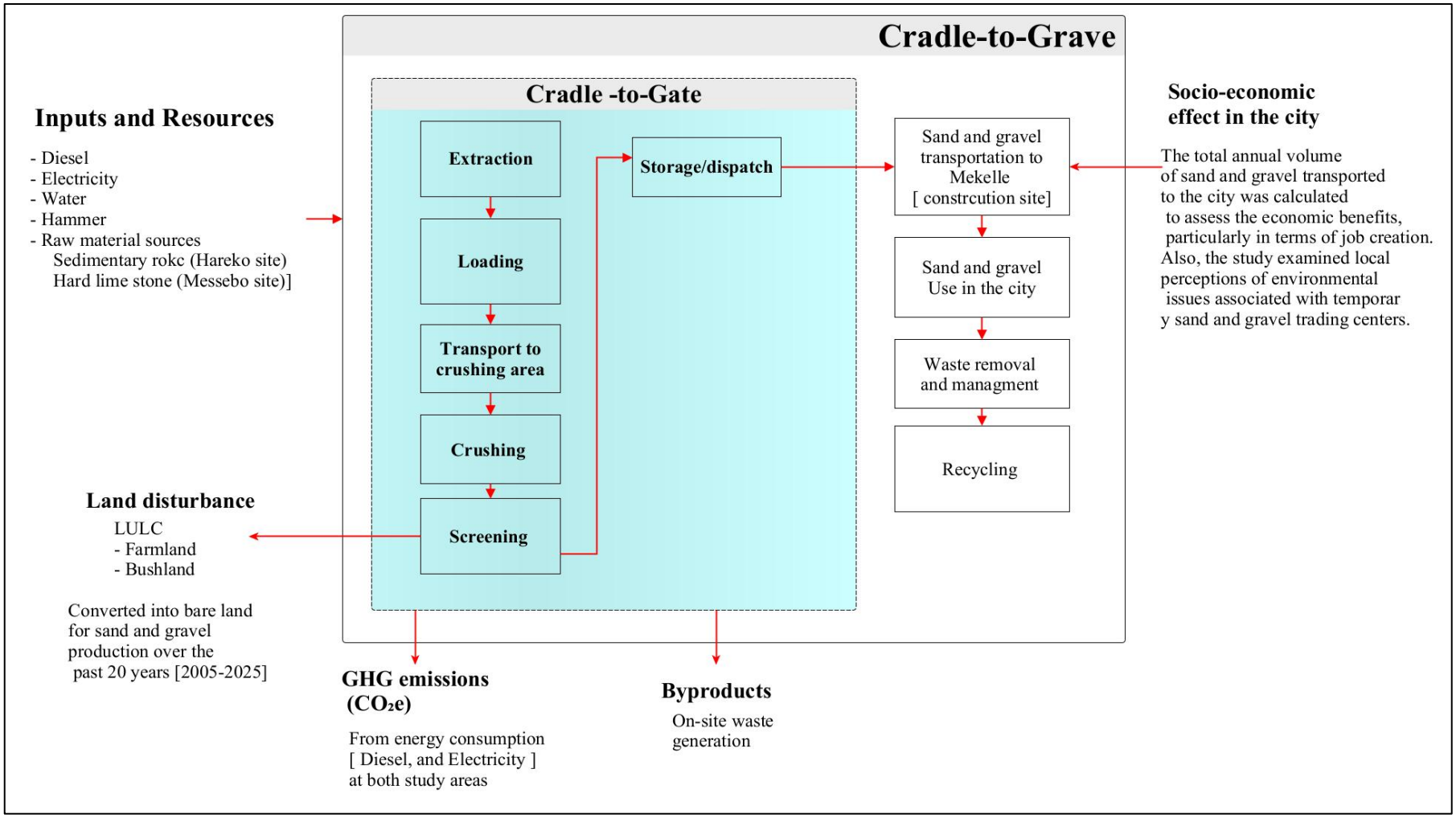


Figure 3. 3: Cradle-to-Gate of sand and gravel production in Hareko and Messebo

Source: Conceptually developed by the researcher (2025)

3.3.3.2 Parameter measurement and calculations

3.3.3.2.1 Estimating volume of construction material flow

Material throughput (t/year) was calculated using reported annual production volumes and an assumed constant bulk density reflecting typical sand and gravel material properties. The bulk densities of 1.6 ton /m^3 for sedimentary rocks (Manger, 1963) and 2.6 ton /m^3 for hard limestone (Oates, 2008), used for mass conversion purposes. Besides, key operational variables were also identified in both study areas, which included daily working hours and monthly and annual working days. The type and efficiency of crushers employed at each site were also considered, given the standards example, for mobile crushers (Backman & Minav, 2025), against context specifics, as they directly influenced the yield of usable products. Data on these variables were collected directly from production sites through in-depth interviews with firm owners and were verified against annual reports and contractual records. Also, broader factors known to affect gravel and sand production were taken into account when developing the simple arithmetic calculation and context-specific formulas. These included proper feed rate data collection from each site to ensure operation at design capacity, prevent over- or underloading, and maximize productivity.

The estimation of material flow was structured to quantify both usable products and by-products, allowing for an assessment of production efficiency and the potential for circularity in material utilization, although such practices were not observed at either site. Using site-level data, including daily working hours (8 hours/day), monthly working days (22 days/month), non-working months per year (2 months/year, July and August), and total annual working days (220 days/year) which were consistent across both study areas the following simple arithmetic formulas were applied to estimate gravel and sand production.

Daily production capacity

$$[D_p] = \text{Measured value from site per 8 hours of daily working time . eqn (2)}$$

Monthly production

$$[M_p] = \left[D_p x M_d = D_p x 22 \frac{days}{month}\right] \text{.. ....eqn (3)}$$

Annual production

$$[A_p] = \left[Y_d x M_p = 220 \frac{days}{year} x M_p\right] \text{.....eqn (4)}$$

Useful product (sand and gravel)

$$[U_p] = [T_c x\ E] \ldots\ldots \text{eqn (5)}$$

Total mass of sand and gravel produced (ton/year)

$$[M_t] = \left[\begin{matrix} Total\ Output\ sand \\ (useful + not\ useful) \end{matrix} x1.6 \frac{t}{m^3} \right] \ldots\ldots \text{eqn (6)}$$

$$[M_t] = \left[\begin{matrix} Total\ Output\ sand \\ (useful + not\ useful) \end{matrix} x2.6 \frac{t}{m^3} \right] \ldots\ldots \text{eqn (7)}$$

Total average sand and gravel produced t/year)

$$[A_t] = \left[\frac{Total\ sand\ production + Total\ Gravel\ production}{2} \right] \ldots\ldots \text{eqn (8)}$$

Where:

M_p = Monthly product (tons/month or m3/month)

D_p = Daily product (m3/day-measured)

M_d = Number of monthly working days (days/Month).

H_e = Effective working hours per day

A_p = Annual product (m3/ year)

Y_d = Total working days per year (days /year)

Tc = Total raw material crushed/produced (m^3/year)

E = The conversion efficiency, based on site data, was (75% sand and 95% gravel)
On average, 8**5%**, meaning that 85% of the total crushed raw material
was converted into usable product.

***Assumptions and justifications*:** This operational consistency was assumed across the study period, including daily working hours, annual operating days, crusher types, equipment efficiency, and material characteristics. Applying uniform assumptions across all the sites also helps to minimize systematic bias and enables comparative assessment of environmental performance among quarries. Thus, accordingly, using the above relationships and the measured data from both sites, the volume of manufactured sand has been converted into useful sand, along with the gravel produced at each site (Table 3.2), and has been calculated as detailed in Annex VI.

3.3.3.2.2 Estimating GHG emissions from material flow

Next to the collection of input-output data using the LCI method, the greenhouse gas (GHG) emissions from the manufactured sand and gravel production process were estimated under the framework of the stated system boundary. The emission factors for diesel combustion and electricity

use were adopted from the IPCC Guidelines for National Greenhouse Gas Inventories. These factors are widely used in LCA studies and provide robust default values in the absence of site-specific emission measurements. Their application ensures methodological consistency, transparency, and comparability with other studies in the construction materials sector. Well-to-wheel diesel emission factors and simple arithmetic calculation methods, in line with EN 15804+A2, were used to estimate greenhouse gas emissions. In this case, the major inputs at the project site included the total diesel and electricity consumed, the volume of materials crushed, the bulk density of both materials, and the well-to-wheel diesel emission factor(USEPA, 2020). Also, the Ethiopian grid's emission factor from the GHG protocol/climatic data is reported as 0.0164 kg CO_2e/kWh (Climatiq, 2017), and for diesel, it is 2.65kg CO_2e/L. Accordingly, the CO2e was calculated as follows, with a detail presented in Annex-II(b).

Electricity CO_2e

$$CO2_{electric} = [\text{Annual Electricity consumption kWh}]x[\text{Grid EF}] \quad \text{eqn (9)}$$

Diesel CO_{2e}

$$CO2_{diesel} = [\text{Annual diesel consumption in litter }]x[\text{Emission factor for diesel}] \quad \text{eqn (10)}$$

$$CO_2e \text{ per tonne} = \frac{[\text{Annual diesel consumption(L)}]x[\text{EF for diesel}]}{\text{Annual production (t)}} \quad \text{eqn (11)}$$

The total annual operational CO_2e

$$\text{Total } CO_2e = CO2_{electric} + CO2_{diesel} \quad \text{eqn (12)}$$

The electricity consumption was calculated as the total electricity used by the electrically powered crushers in both study sites. Similarly, the annual diesel consumption was determined as the total diesel used by trucks, excavators, crushers, impactors, screening machines, water collection trucks, and loaders within the sand and gravel production compounds.

3.3.3.2.3 Estimating water spraying and efficiency for dust supervision

Freshwater use for dust suppression (m^3/year) was measured on-site and normalized to production output following EN 15804+A2 guidance. According to the technical manuals and guidelines of the U.S. EPA (U.S.EPA, 2023), control efficiency measures how much or the percentage of dust emissions is reduced by water spraying, while water intensity indicates the total volume of water used per unit of material produced. Besides, the uncontrolled dust emission was assessed using equation (13), which was calculated as 1,085.57lb/year, though applying the control efficiency factor (CE)

0.006lb/ton for watering, and 1 lb = 0.454 kg as per the US EPA AP-42. Although AP-42 does not provide explicit values, wet suppression typically reduces particulate emissions by 50–90% (70% on average), depending on application and particle sizes. Next, the controlled emission is calculated using Eqn (14), which is 325.67lb/year as detailed in Annex 1.

$$U_e = [EF]x[M_t] \quad \text{..... eqn (13)}$$

$$C_E = [Ue]x[1 - C_e] \quad \text{..... eqn (14)}$$

$$A_r = U_e - C_E \quad \text{..... eqn (15)}$$

$$\boldsymbol{C_e} = \left[\frac{\text{Absolute reduction}}{\text{Uncontrolled dust emission}}\right] \times 100\% \quad \text{.....eqn (16)}$$

Where:

C_E	Controlled emission
EF	Emission Factor
A_r	Absolute reduction
U_e	Uncontrolled Emission
C_e	Controlled efficiency (i.e., 70%)

The land use land cover change impacts were quantified using GIS-based mapping for the last 20 years (2005 -2025), to track the amount of annual disturbance per study area, with no subsequent rehabilitation implemented. The quarry byproducts, mainly unusable fines, were incorporated into the study as on-site waste disposal, thereby contributing to land occupational impacts. The functional unit was defined as 1 ton of product at the quarry gate. System boundaries were restricted to modules A1-A3 (cradle to gate) as in Figure 3.2 While the study does not include excavated topsoil, downstream transportation, or use phase impacts, and therefore does not encompass all mandatory impact categories specified under EN15804+A2, it provides a transparent and robust characterization of the principal environmental indicators, namely greenhouse gas emissions, land disturbance, waste generation on site, and water use. Furthermore, the study accounted for mitigation measures, such as dust supervision via water spraying, and the socio-economic contribution of quarry operations, in terms of local employment generation.

3.3.5 Data analysis methods used

3.3.5.1 Descriptive statistical analysis

The study used statistical software (STSTA) to analyze the quantitative data from survey questionnaires. Excel was also employed for the development of graphs and tables. Qualitative data were analyzed contextually, with direct quotes from interview respondents incorporated to provide deeper insight. These descriptive analyses, including the assessment, were critical in establishing the socio-economic footprint of manufactured gravel and sand production areas, particularly in terms of short-term job creation, and helped identify patterns that guided further analysis.

3.3.5.2 ArcGIS tools

The different ArcGIS tools were used for final data analysis including image classification, change detection, transition matrix analysis, spatial overlays, a rea and rate -of -change computation, and accuracy assessment of the three LULC changes as presented hereunder.

- ***Image pre-processing*:** After data acquisition, the imagery was preprocessed to ensure suitability for analysis by correcting distortions and improving image quality, visual interpretation, and spectral separability (Chuvieco, 2020). The Landsat images were preprocessed using ENVI 5.2 and ArcGIS, including layering, stacking, georeferencing, resampling, and projection (Maini & Aggarwal, 2010). All spectral bands were stacked into a single composite image (Srivastava et al., 2012), and datasets were projected to WGS84 UTM Zone 37 North. Pixel values were standardized to enable accurate comparison and change detection, and the making techniques were applied to extract the study area.
- ***Image correction and enhancement:*** To improve image quality and analysis (Vermote et al., 2016); the two correction methods, radiometric and geometric correction, were applied. Radiometric was used to improve brightness and reduce noise and atmospheric effects by converting digital numbers into surface reflectance through atmospheric correction and image calibration (Lillesand et al., 2015). This included converting digital numbers to top-of -atmosphere radiance and reflectance (Ha et al., 2020). All images were level 1 data, meaning they were already geometrically corrected and orthorectified. Atmospheric correction was further applied using the dark pixel subtraction method (Chavez Jr, 1988). Reflectance calibration, producing unitless values between 0 and 1, enabled comparison (Micijevic et al., 2021), and mosaicking of images from different Landsat sensors (Chander et al. 2009).

- ***Image classification:*** This step involved the supervised classification of the landscape into distinct LULC classes. The main LUCLC categories/types identified were Farmland, bushland, and bareland from manufactured sand and gravel special expansion over the last 2 decades. False color composite images were created using band combinations 4-3-2 for TM and ETM+ images and 5-4-3 for OLI images(Lasisi et al., 2017). Based on spectral responses and field observations, three LULC types were identified, with their descriptions provided in the table.

Table 3. 3: Land use types in both study areas

LULC types	Description
Bare land	In the context of bare land expansion, it often represents recently cleared or disturbed land that has been converted from farmland and bushland for sand and gravel production, and is characterized by low vegetation coverage and distinct spectral reflectance in satellite imagery. This definition aligns with standard land-cover descriptions that classify bare areas as having minimal vegetative cover, often less than one-third of the surface (Mekonnen et al., 2018).
Farmland	Comprises lands used for temporary crops, especially plots that alternate between growing and fallow phases or are dominated by seasonal agricultural cycles. This includes cultivated fields and grasslands used for food production. Several land-use/cover classification schemes refer to agricultural lands in this way(Eggen et al., 2016).
Bushland/Shrub land	Describes areas covered by shrubs, small trees, and bushes, often mixed with grasses. For instance, studies define shrubland as having greater than 20% shrub cover and low tree canopy cover (Mariye et al., 2024).

- ***Accuracy assessment:*** Accuracy assessment is crucial in LULC classification, as it helps identify errors arising from preprocessing, interpretive techniques (manual and automated), image systems, and sampling and accuracy calculation methods (Foody, 2002). Because a map user is concerned with the map's dependability or its accuracy in reflecting the actual conditions on the ground (Congalton & Rekas, 1985). Thus, classification accuracy is commonly expressed as the percentage of correctly classified map areas compared with reference and ground truth data (Story & Congalton, 1986). Accuracy is typically derived from sampling results presented in an error (confusion) matrix, where reference data were compared with classified data (Rwanga & Ndambuki, 2017), to rectify the calculated Kappa statistic strength of agreement in the table below.

Table 3. 4: Rating criteria of Kappa statistics

Kappa Statistics	Strength of Agreement
<0.00	Poor
0.00-0.20	Slight
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Substantial
0.81-1.00	Almost Perfect

Source: Adopted from (Rwanda e.t.l,2017)

Various measures, such as overall accuracy, producer's accuracy, user's accuracy, and kappa coefficient, were calculated to evaluate classification accuracy and compare independently classified images to detect land cover changes (Liu & Mason, 2016). The concepts and their calculations are well-documented in the literature (Congalton, 1991; Congalton & Mead, 1983; Hudson, 1987; Smits et al., 1999).

$$K = \frac{N \sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} (x_{i+} X\, x_{+i})}{N^2 - \sum_{i=1}^{r} (x_{i+} X\, x_{+i})} \quad \text{..... eqn (2)}$$

Where:

K Kappa coefficient
N is the total number of sites in the matrix
r is the number of rows
xii is the number in row i and column i
x+i is the total for row i
xi+ is the total for a column

This formula is used to compare independently classified images to identify land cover type changes, with the 'K' value calculation outlined accordingly. Hence, Kappa analysis yields a Khat statistic (an estimate of KAPPA, equation 1) that is a measure of agreement or accuracy (Jensen, 1996). When the remote sensing-based data's overall accuracy assessment exceeds 80%, which signifies a notable precision level in identifying land use and land cover that is in harmony with verified ground data (Abbas & Jaber, 2020).

- ***Change detection:*** Change detection of three land use and land cover classes was conducted using post-classification comparison or change vector analysis techniques, with post-classification comparison providing the highest accuracy. This approach, based on the MLC algorithm and Landsat data, involved converting classified raster images into vector layers to calculate and present LULC changes for each class. Before finalizing the LULC map, reference data were compared with the classified map using a confusion matrix, and statistical accuracy measures were applied to evaluate map quality, with necessary corrections made during mapping (Sun et al., 2009). Finally, the LULC changes analysis over two decades was integrated with the environmental impacts from rural-urban linkage in terms of manufactured sand and gravel utilization. The LUCL change analysis outcome was also supported by the ground-based observation and interviewed residence ground-based data.

3.3.5.3 Life cycle assessment under the cradle -to-gate system boundary

The life cycle assessment was employed to quantitatively analyze the environmental impacts associated with the input-output module of the manufactured sand and gravel, which aligns with the En 15804 +A2 environmental standards (EN 15804, 2012). The impacts generated at the production level include energy use and emissions. This method also supported the identification of processes with the highest impacts, enabling the assessment of critical processes contributing to environmental burdens and integrated with the social impacts and existing mitigation measures.

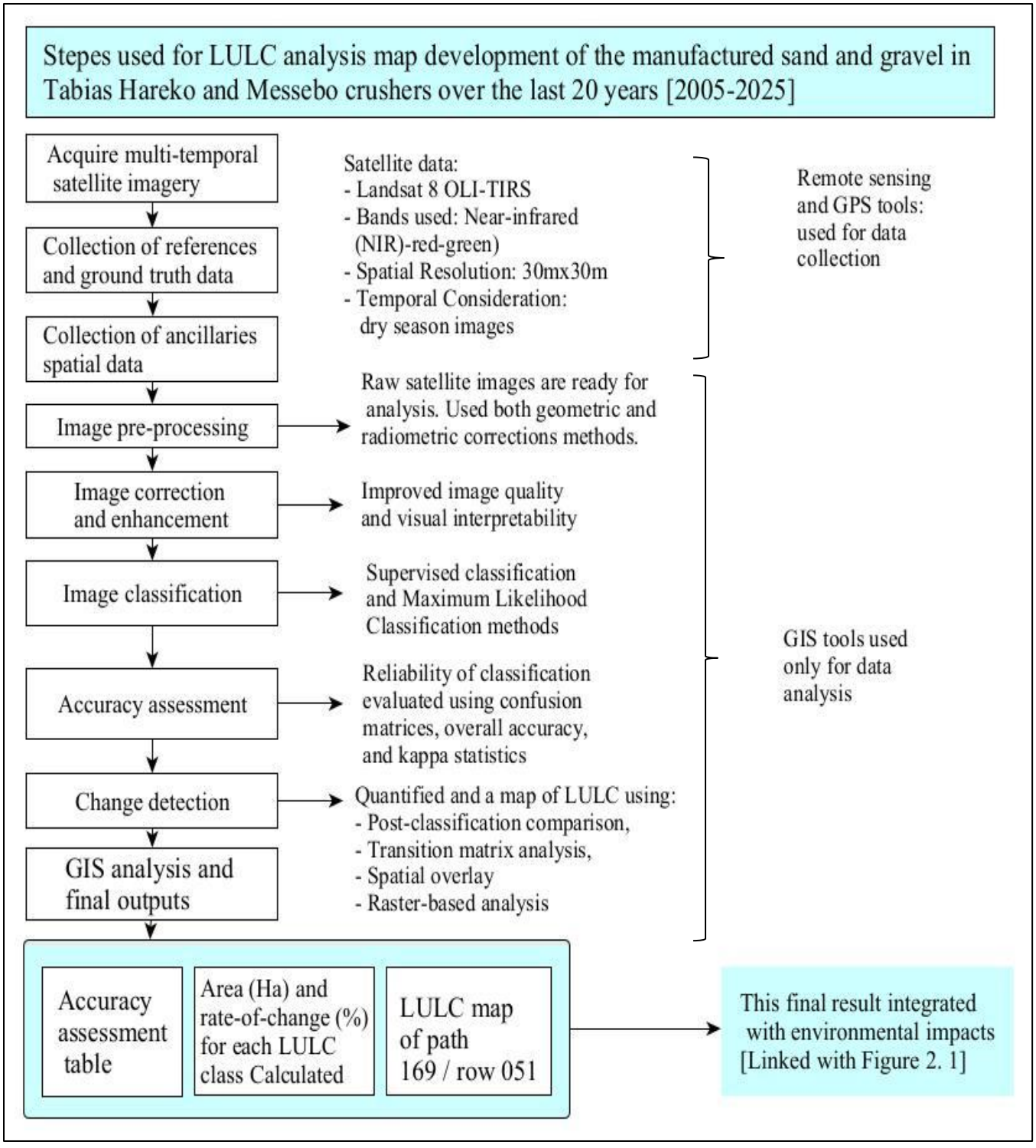


Figure 3. 4: Manufactured sand and gravel data collection and analysis flow map using GIS and RS geospatial techniques or tools

CHAPTER FOUR: RESULTS AND DISCUSSIONS

The major findings of the study focused on three main specific objectives and their alignment with other related research findings areas, summarized below.

4.1 Volume of construction material flow

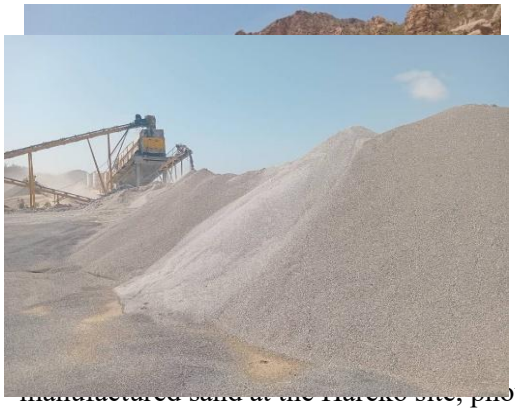
4.1.1 Manufactured sand and gravel overall aim analysis

According to ground observations and discussions with residents and crusher owners, the findings also indicated that the rural and urban sampled respondents were benefiting from the production, while the environmental effects had become a persistent problem. However, following the devastating two-year conflict in Tigray, clear issues of data inconsistency and reliability were observed at both the site and main office levels, potentially affecting research quality. This result is consistent with the findings of (Bruton et al., 2000), which showed that inconsistent data and unreliable measurements can cause errors, bias, and misinformed decisions, undermining research trustworthiness.

Thus, the research was not fully capturing the urban–rural linkage in terms of local construction material use before the war, except for land use and land cover changes, which were tracked over the last 20 years using GIS and RS techniques. The two major local construction materials developed and transported to Mekelle city in this study are sand and gravel developed through sedimentary rock crushing and hard limestone, respectively, using diesel and electric-powered stationary and mobile crushers.

4.1.1.1 Volume of manufactured sand

The study findings indicated that approximately 88,880 m³ of sedimentary rock were crushed within the study area using both diesel- and electricity-powered crushers at Messebo and four crushers at Hareko. Of this total, an estimated 75 percent (66,660m³) was converted into usable construction-grade sand. In comparison, the remaining 25 percent comprised fine dust and oversized fragments that were stockpiled, backfilled, or reused for site leveling purposes. Despite the steady production volume, local market demand for manufactured sand declined mainly during the rainy season, when rivers are filled with natural sand. This was largely



manufactured sand at the Hareko site, photo taken by the researcher, June, 2025

due to the manufactured sand's very fine grain size and relatively weak structural integrity. When exposed to prolonged sunlight and wind, the fine particles tended to further break down and resemble fine soil, thereby reducing their suitability for structural applications such as concrete and masonry works. Respondents from the urban area, who have experience and skills in the construction sector, particularly in plastering, explained that

> *"Even though manufactured sand is a suitable alternative to river sand, its demand decreases when river sand is more available due to its finer particles, higher cement requirement, poor water retention, and potential impact on concrete durability. Production centers are expected to improve particle size to meet user needs and the national standards of not less than 0.15mm."*

Figure 4. 2: Sample photo of the manufactured gravel at the Tabia Messebo sites, photo taken by the researcher, June, 2025

This finding is directly consistent with (Tan et al., 2023), which demonstrated that manufactured sand concrete maintains comparable bending strength and durability to river sand concrete when used within the 0.15–4.75 mm range.

> *"In the city, crushed sand is now used as an important substitute when river sand is hard to find, helping construction work continue without interruption. Early tests show that when some of the cement or river sand is replaced with crushed rock dust, the concrete becomes harder to mix and less smooth to work with as more dust is added. However, using a moderate amount of crushed dust can actually make the concrete stronger and last longer. This means builders may need to adjust the mix or test it more to make sure it has the right balance of strength and workability."*

This ground-based quote is also consistent with other studies of (Rafi and Aziz, 2022), who reported that moderate replacement of river sand with crushed rock *or* stone sand around 20–50% enhances concrete strength, stiffness, and durability while reducing water absorption.

Manufactured sand has become an essential alternative to river sand in urban construction, particularly during dry seasons or when the extraction of natural river sand is very limited and costly. As noted by local construction engineers, this adaptation is crucial in the absence of accessible river sand. However, the manufactured sand often exhibits particle size variations, with some particles measuring as small as 0.15 mm or smaller.

To mitigate potential issues such as increased dust formation and reduced particle cohesion, moisture control practices are essential. These include regularly spraying water over stockpiles and providing shade to preserve the sand's moisture content until use. This idea is also aligned with the experimental investigation result of (Nguyen et al., 2022); blending manufactured sand with river sand can influence the mechanical properties of concrete, highlighting the importance of managing the moisture content in such mixtures. This indicates that the interviews with construction engineers confirm that these moisture control practices are effective local adaptation techniques. They help minimize dust formation and preserve particle cohesion, demonstrating the technical ingenuity of local producers in responding to material limitations and climatic conditions. These low-cost, context-specific practices not only enhance the usability of river sand but also contribute to sustainable construction practices by reducing reliance on natural river sand. Furthermore, this also supports the funding of (Mamo et al., 2024), the result showed that utilizing alternative fine gravel can ensure a circular economy in the construction industry and reduce the consumption of natural river sand by approximately 30%.

The transportation pattern of the manufactured sand was found to be unregulated and consumer-driven, with most buyers organizing their own logistics directly from the crushing sites. In some instances, crusher operators delivered sand to clients upon request, particularly when bulk orders were made. The average transportation distance ranged between 10.5 and 45 kilometers, depending on the proximity of the construction site to the quarry and road accessibility. Delivery was typically conducted using medium-capacity diesel trucks with 16 m^3 loading capacities, and trip frequency varied according to construction season and demand level. This uncoordinated transport system, where vehicle loading, fuel consumption, and delivery frequency were not systematically tracked, supported the adoption of a cradle-to-gate boundary in the analysis. This finding is also supported by the recent study by (Teku,2025), which reported that covering all activities from raw material extraction to the delivery of manufactured sand at the construction site or batching plant. Within this boundary, the three sampled sand and gravel trading centers in the city (Mekelle) directly purchased 5 to 50 truckloads (equivalent to 80 cubic meters per month and 800 cubic meters per year) from the production site, which corresponded to 12 % per year of the useful sand production. Although the manufactured sand from sedimentary rock was less preferred than river sand due to its fine texture and susceptibility to weathering, it played a crucial role in maintaining the continuity of local construction activities throughout the year. In the marketplace (detailed in section 4.2), the near-total

absorption of available output indicates that demand for non-riverine sand has become well established, especially during the dry season, when riverbeds are depleted of flood-borne sand and trading centers depend heavily on alternative sources. However, the price variations compared to river sand reveal that buyers remain highly sensitive to product quality parameters such as particle size, texture, and cleanliness. These results highlight the technical and operational resilience of local crushing enterprises and emphasize the importance of enhancing local material management practices to optimize the quality and performance of sedimentary rock–derived manufactured sand within a cradle-to-gate production framework.

This untapped potential in Tigray, which uses manufactured sand rather than river sand, has already created both environmental and social impacts and risks. The key points observed include: entails substantial energy use and emissions, land use and land cover change, and its extended environmental degradation from a lack of mitigation measures. Because the operation did not recycle by-products, the solid waste accumulation posed risks of land degradation, dust release, and inefficient resource utilization. For instance, during the study period, the number of active sand crushers was four. Still, the production capacity of the three smaller crushers was minimal and mainly served nearby local markets such as Adigudom. Nevertheless, these crushers contributed to temporary job creation while also causing environmental problems due to increased diesel consumption and changes in land use and land cover over the past 20 years. Besides, more than five investors submitted proposals to the Tigray Agency for Environmental and Climate Change Protection to install additional sand crushers at the site, focusing on the physically observed, rock-dominated sedimentary formations in highly suitable zones. The main concern was that, although demand for construction materials was increasing, attention to environmental and social impacts and the implementation of risk mitigation measures were almost entirely neglected at all administrative levels. A similar trend has been observed in other developing regions where sand mining oversight remains weak (Akanwa et al., 2025). Furthermore, because no detailed scientific study had been conducted to assess the site's potential for sustainable sand production without degrading the surrounding landscape, and because consultation with local communities was minimal from the outset, the risk of irreversible social and environmental damage was high, which is consistent with the finding of (Vélez-Torres et al.,2024).

4.1.1.2 Volume of manufactured gravel for construction

The production of local construction gravel is obtained by crushing hard limestone with electrically powered mobile crushers. Only three crushers with significant variance in production capacity and time of establishment were found to be functional, supplying gravel to the city's construction market. The average total production was estimated at 84,480 per year, as detailed in Table 4.1 and its detailed calculation in Annex II (a). The production process was relatively efficient, with only 5% of crushed stone becoming byproduct output, which was dumped around the crusher sites without any immediate or long-term mitigation measures.

The primary reason for the lower byproduct was that operators selectively transported high-quality stone, converting most of the material into usable output with minimal loss. However, this approach may not be sustainable over time, as the most accessible material could become depleted. This may lead to intensified cutting and filling activities, resulting in further bushland loss and associated adverse effects such as land degradation, reduced vegetation cover, and the decline of key native species, including honeybee flora. These findings are consistent with those of (Prakash and Budhwan 2024, Yihdego et al., 2018).

Individuals who have asked for a temporary place for local construction material trading with the sub-city municipal in the city's temporary sand and gravel trading centers purchased approximately 1,120 cubic meters of gravel per annum, directly from the sources. Market demand for the produced gravel remained strong and consistent, and no major issues were reported regarding particle size distribution, supported by the uniform quality of gravels classified as 00, 01, and 02, though there is no regulation for crushed particle sizes, as it varies based on local demand. However, similar to the sand production, gravel production created environmental and social impacts over the past 20 years (2005,2025) in terms of land use and cover changes, such as reduced farmland, land degradation, and vegetation loss, as detailed in section 4.2.

Table 4. 1: Summarized volume of manufactured sand and gravel across 7 study crushers

Input category	Working periods			Production			Production efficiency (%)	Useful production m3/year
	Daily working hours/day	Monthly working days/month	Yearly working days	Daily production measured m^3/day	Monthly productionm3 /Month	Average Yearly production (m3/Year)		

Manufactured sand for construction (Hareko)	8	22	220	404	8,888	88,880	75	66,660
Gravel for construction (Messebo site)	8	22	220	384	8,448	84,480	95	80,256
Total Average	8	22	220	394	8,668	86,680	85	73,458

Source: Survey data result, 2025

4.2 Economic and environmental impacts from local construction material flow

Across the two production tabias, a total of 17 crushers were identified, five for sand production at Hareko and twelve for gravel production at Tabia Messebo. Still, only 41.2% were operational (three at Messebo and four at Hareko). Reduced functionality was largely due to the two-year war and its lingering effects, including spare part shortages, high maintenance costs, fuel scarcity, and limited access to loans, which severely affected material output, socio-economic performance, and data reliability. Despite these constraints, the crushers employed approximately 250 rural and urban workers, maintaining a sustained supply of construction materials to the city. Environmental and socio-economic conditions observed at quarry sites and selected urban sampling points are assumed to represent typical rural–urban linkages in the study region. Finally, the analysis assumes a lack of circularity within the system boundary; quarry by-products are considered to be discarded without significant reuse or recycling, reflecting current operational practices at the study sites.

The key environmental impacts under the cradle-to-gate system boundary included greenhouse gas emissions from diesel and electricity use, quantified per ton of material produced to allow comparisons across sites and scenarios. Farmers' perceptions revealed a clear disconnect between formal mitigation measures and actual practices on the ground, while environmental and social pressures were observed at temporary distribution centers within the city, and by-product dumping contributed further to local environmental impacts. The economic assessment indicated that the crushers supported job creation within the study areas and the city, provided community-level economic support from investors, and facilitated rental payments to farmers who leased their farmland, all of which was evaluated in relation to local proclamations and policies.

Figure 4. 3: Site observation in both sites and on-site data collection, photo taken by the researcher, June, 2025

4.2.1 Socio-economic impacts

4.2.1.1 Gender (sex) of respondents

Table 4.2 indicates a clear male dominance among sampled respondents, reflecting the limited female participation in direct crusher operations. The 70:30 male-to-female sample ratio ensured female perspectives were included. Women were mainly involved in ancillary and supervisory roles, such as food preparation, vending, operating small refreshment stalls, handling cash, organizing production schedules, and overseeing minor production activities. Men, on the other hand, carried out physically demanding tasks, including crushing and loading.

The observed gendered division of labor had multiple implications. First, it constrained women's direct engagement in high-income activities, yet their involvement in ancillary and organizational roles contributed significantly to household income and livelihood diversification. Second, it revealed socio-cultural norms that shape labor allocation in rural production sites, indicating potential barriers to increasing female participation in direct production tasks. These findings suggest that interventions targeting skill development, workload sharing, and supportive infrastructure could enhance women's

participation in higher-value activities, improve overall site efficiency, and strengthen household economic resilience.

Table 4. 2 The sex of the sample respondents, rural and urban residents

Sex	Freq.	%
Female	24	30%
Male	56	70%
Total	80	100%

Source: Survey data, 2025

4.2.1.2 Age of respondents

As presented in Table 4.3, 51% of the respondents were in the age group of 31-40 years, except for those aged 41 years and above. This age group indicates that the demanding nature of the manufactured sand and gravel production requires early to mid-adulthood due to physical strength, productivity, and active engagement. According to ground observation findings, respondents aged 41 years and above were engaged in supportive roles, particularly guarding production sites. This suggests a shift toward less physically intensive work with age. While participants among those under 30 years old were observed to be low, next to those above 41 years old. This was observed in relation to the alternative employment choice offering better wages, flexibility, and improved working conditions. These findings indicate that manufactured sand and gravel production depend on middle-aged workers for core production activities. This age distribution has implications for labor allocation, workforce sustainability, and the long-term planning of production operations, emphasizing the need to balance physical demands.

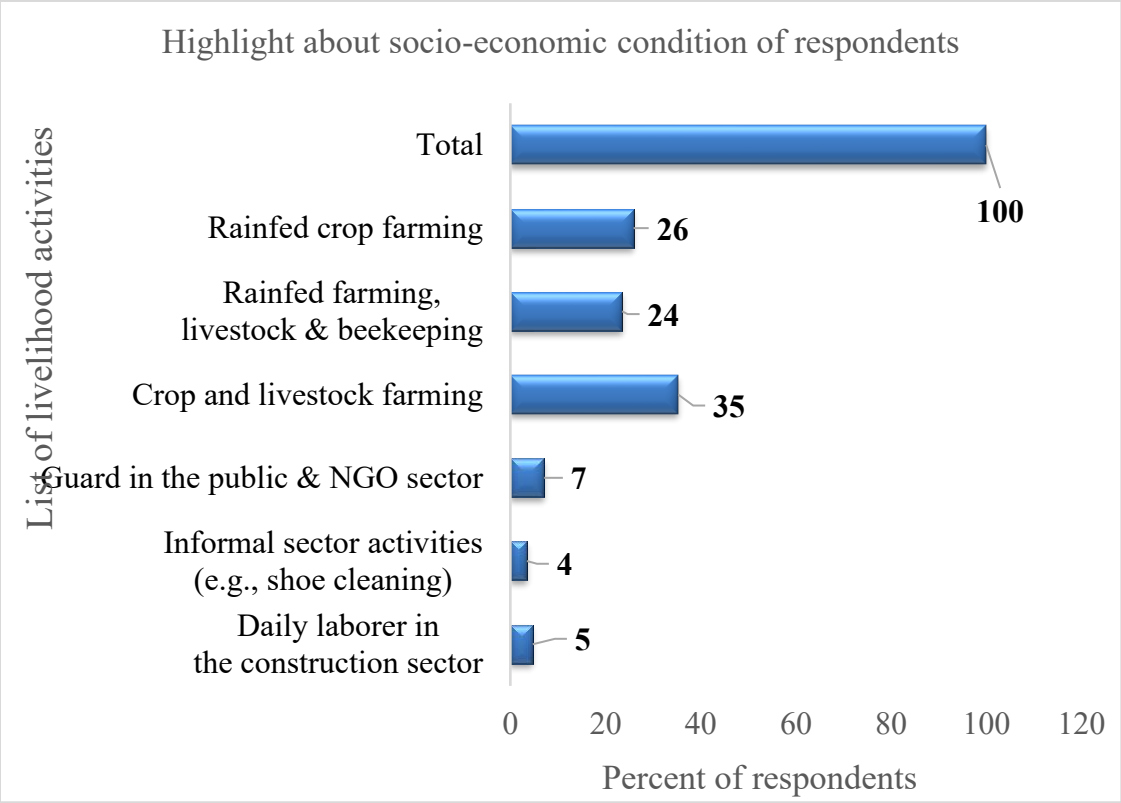
Table 4. 3: Age of sample respondents, rural and urban residents

Age categories	Freq.	%
19-30	33	41%
31-40	41	51%
≥41	6	8%
Total	**80**	**100%**

Source: Survey data, 2025

4.2.1.3 Highlight about the socio-economic profile of the respondents

Figure 4.4 shows that the socio-economic conditions of the sampled respondents were largely dominated by agricultural activities, with 85% engaged in farming. Crop and livestock farming is the most common livelihood, representing 35% of respondents, followed by rainfed crop farming (26%) and rainfed farming with supplementary activities (24%). This indicates a heavy reliance on rainfed agriculture, which exposes households to climatic vulnerabilities such as drought and irregular rainfall, as also explained by the respondents. A smaller portion of respondents from the urban study areas were employed outside agriculture, with 7% working as guards in the public and NGO bureaus, 5% as daily laborers, and 4% engaged in informal sector activities, reflecting limited income diversification. The findings highlight the need for interventions focused on climate-resilient agriculture, income diversification, and the expansion of formal and informal employment opportunities to improve livelihoods and reduce vulnerabilities among the rural and urban populations.



Source: Survey data, 2025

Figure 4. 4: Highlight on socio-economic profiles of sampled respondents

4.2.1.4 Socio-economic analysis: local construction material flow

4.2.1.4.1: Positive socio-economic impacts of manufactured sand and gravel

a) Socio-economic impacts at crusher sites (Rural)

Short-term job creation: At the rural quarry and crushing sites, the construction material sector constitutes a major non-farm livelihood opportunity. The field observation and 84% of the total sampled respondents and interviews, including operators, indicated that each production site employs between 60 and 81 workers directly in extraction, crushing, and loading operations, with an age range presented as in Table 4.4.

Table 4. 4 Average wage rate per employee per study area

S/n	Parameter	Symbol	Hareko site (Sand)	Tabia Messebo site (Gravel)	Remark
1	Direct employees per site (sum of 4 crushers in Hareko and 3 crushers in Messebo site)	A	81 (1 Female)	60 (3 female)	Total labor, the sum of the operators, loaders, sorters, drivers, managers, guards, and food makers per crusher
2	Average daily wage per employee	B	886	886	Site interviews + payroll/payment sheet
3	Average total daily wage per crusher	Y	71,766.0	53,160	$Y = [a] \times [b]$ the same, for crushers
4	Average total daily wage circulation for all crushers	X	71,766.0	53,160	$X = [Y] \times [1^{***}]$, which was found same for crushers

Source: Survey data, 2025

The tabular data shows that a total of 141 daily employees across both sites provided a stable source of income, particularly during the agricultural off-season. Daily laborers, including site guards, reported engaging in crusher operations as a coping strategy for declining crop productivity due to rainfall variability and land scarcity. Employment was prioritized for residents who leased their farmland for crusher installation, demonstrating that rural sand and gravel production serves both as an income stabilizer and as a driver of local economic circulation, while maintaining a steady supply of construction materials to urban centers.

The average gross daily wage of 886 ETB/day was lower than that of typical agricultural labor during harvest (975 ETB/day), yet households continued participation due to the proximity of production sites, which reduced transportation and meal costs and allowed income diversification. Wage similarity across crushers in the two rural sites masked significant differences in benefits such as safety equipment, PPE, overtime payments, and performance incentives, which were largely determined by crusher size, management capacity, and operational scale. Larger, well-managed crushers offered better welfare packages, enhancing labor motivation, retention, and safety performance, while smaller or newer crushers provided limited or no additional benefits, affecting workers' job satisfaction and livelihood outcomes.

Technological limitations were a major constraint on productivity. Most crushers were semi-mechanized diesel-powered units operating below capacity due to mechanical downtime, poor maintenance, limited technical expertise, rising diesel prices, and supply shortages. Interviewed owners reported that electric-powered crushers increased output by 15–25% and reduced fuel dependency, but unreliable rural electricity and limited access to credit hindered adoption. Evidence from recent case studies indicates that electric crushers can reduce energy use per ton by 35% and lower dust emissions by more than 60%, highlighting opportunities to improve operational efficiency and environmental sustainability.

Gender inclusivity remained weak, with men representing 97% of employees. Women's participation was limited to roles related to cash handling, resource management, and ancillary services such as food preparation and small-scale vending near crusher sites. These activities provided only a minor, uncertain source of income, constrained by a limited customer base and laborers' low spending capacity. In urban trading settings, sand and gravel operations were entirely male-dominated, reflecting social norms and the perceived physical difficulty of the work, consistent with other studies (TheGlobaleconomy.com, 2024).

Overall, the findings indicate that sand and gravel production provides essential livelihood support and local economic benefits, but operational inefficiencies, limited technology adoption, and low gender inclusivity constrain productivity, labor welfare, and environmental performance. Addressing these challenges through targeted infrastructure investment, improved management, and inclusive

labor policies could enhance both the sustainability and socio-economic impact of rural sand and gravel production.

b) Socio-economic impacts at manufactured sand and gravel trading sites (urban)

The three sampled sand and gravel trading centers purchased materials directly from main distribution hubs and resold them to local buyers based on demand, providing flexible purchasing options that allowed customers to acquire quantities suited to their income and construction needs, from small portions to full truckloads. These operations generated temporary employment for approximately 180 workers per year, with an average daily wage of 800 ETB, though the number of working days fluctuated with construction activity and material demand. This highlights the role of trading centers in sustaining livelihoods and providing income diversification, particularly during periods of agricultural uncertainty.

Trading data analysis result showed (Annex IV) that manufactured gravels and sand were purchased at an average cost of 50,150 ETB per truck and resold at 55,630 ETB per truck (16 cubic meters), while manufactured sand was bought at 32,500 ETB per truck and sold at 42,909 ETB per truck. Price variations were driven by transportation costs, truck rental, and rising fuel prices, reflecting both operational and energy-related considerations. Trading activities were dynamic, with sellers relocating to areas of higher construction activity rather than maintaining fixed centers, which influenced labor demand, operational efficiency, and energy use. On average, the centers earned 15,889 ETB per month from two trucks of sand and gravel, demonstrating their economic importance for local livelihoods despite socio-economic fluctuations and conflict-related disruptions.

Seasonal patterns significantly affected supply and demand; for example, the river sand prices were higher during the rainy season (September–December) due to replenishment, while manufactured sand remained a cost-effective alternative. During the dry season, scarcity and mixing of river sand with clay or shale increased reliance on manufactured sand, illustrating its role as a substitute material that reduces pressure on natural riverbeds. The finer particle size of manufactured sand, which requires more cement in construction, also contributed to price differences. Traders mitigated quality issues and dust emissions by spraying water on manufactured sand, demonstrating practical environmental management strategies that enhance material usability and reduce airborne particulate pollution. This indicates that manufactured sand and gravel played a key role in ensuring a continuous supply, stabilizing local construction markets, and maintaining economic resilience, particularly during seasonal or resource fluctuations. Therefore, these local construction flow when paired with

sustainable management practices and environmental-social mitigation measures such as controlled extraction, dust suppression, and optimized transport, local sand and gravel trading can simultaneously support livelihood security, resource efficiency, and environmental resilience in rural and urban supply chains.

4.2.1.4.2: Negative socio-economic impacts of manufactured sand and gravel

The study identified several significant social impacts and risks associated with manufactured sand and gravel production, including reduced farmland, livelihood losses, health hazards, and cultural disruptions.

Primary impacts

Decrease in farmland: The LULC analysis map over the last 20 years shows a significant reduction of farmland across the study areas. This reduction is also contributing to the decline in farmland size, as 10 ha of farmland owned by 29 farmers has already been consumed for crusher installation, crew camp, and production. This reduction has further led to a decline in crop production and productivity per hectare, although there may be many other factors associated with this. From the direct field observation, the farmlands near the crushers were exposed to compaction from mining machinery and disturbance. This can also contribute to lowering the surface water infiltration capacity of the soil and reducing nutrient uptake by crop roots due to decreased porosity and root penetration caused by compaction problems.

This, together with the dramatic increase in bushland reduction over the last 20 years, has left the area exposed to wind and water erosion and has made it easily stripped of fertile topsoil, directly harming crop production. These findings are also consistent with other scientific results in Ethiopia (Elnourani et al., 2024; Gashaw and Aklilu, 2020; Tegenge, 2022), which show that improper waste dumping from crushers, integrated with their expansion, directly accelerates farmland degradation and loss, intensifying competition over shrinking agricultural land. In addition to these results, the 67 participants, including those who lost their farmland, expressed dissatisfaction, noting that payments for leased farmland did not reflect the long-term value of their land or potential income loss. The decline of farmland size, combined with the clearly observed soil degradation and its on-site and off-site effects, the destruction of grazing land and the removal of essential grazing bushlands, and the loss of the bee flora affecting honey production, are all contributing to reduced livelihood income for farmers. However, further research is needed to quantify these impacts using evidence-based data.

Key informants at the Hareko site reported concerns over soil fertility loss from machinery and compaction, highlighting weak enforcement of regulations. Also, they said:

> *"A formal lease permitted manufactured sand extraction on my farmland, offering payment and jobs for my family, yet it did little to improve our living conditions. Worried about lasting damage to soil fertility from heavy machinery and compaction. This is integrated with weak regulatory enforcement. I approached the investor to pursue a more sustainable approach."*

This shows that crusher dust and excavation activities have degraded topsoil quality and key essential soil nutrients, and that dust settling on crop leaves has directly contributed to crop yield production and productivity.

Secondary impacts

Health risks: Site observations and results from structured questionnaires indicate that crushers release a large amount of particulate matter or dust into the local air. Observations showed that workers lacked proper personal protective equipment, relying on improvised coverings such as mattresses, while intermittent water spraying limited dust mitigation. Workers inhaled dust continuously over periods lasting weeks and sometimes months, with greater effects among daily workers who have long-term conditions such as asthma. Besides, 100% of employees or daily laborers across the study areas reported eye redness, itching, and watering as the most persistent problems at the crusher sites, while skin dryness and rash were also common among nearby residents. Stress, nighttime sleep disturbance, and ringing in the ears were also frequently reported impacts of the crusher's operations. These results also aligned with other related scientific research in Ethiopia (Ahadzi et al., 2020; Asgedom, 2023; Ashuro et al., 2023; Endalew et al., 2019; Farnham et al., 2020; Upadhyaya,2021), which reported that residents and workers near construction material mining areas in Africa, particularly Ethiopia, face significant respiratory and health risks, exacerbated by dust, blasting, and limited protective measures, even though these activities support rural livelihoods.

Figure 4. 5: Air pollution from dust particles at the manufactured gravel production sites, photo taken by the researcher, May, 2025

The study also highlighted that the continuous dust and particle matter exposure that animals inhale while grazing nearby causes respiratory problems, especially in young animals. Residents also explained that wild animals and livestock do not stay near crusher sites, particularly during operation times, and observed signs of shock and fear when crushers are operating and crush large stones. Besides, rural dwellers who participated in the study reported that grazing lands and plants with settled dust become less palatable. Settled crusher dust can also lower photosynthetic efficiency and plant growth by blocking stomata, affecting flora diversity and quality, and reducing light interception.

This indicates that ingesting contaminated feed can lead to long-term health effects. Dust can also alter local soil PH and nutrient balance, reducing nitrogen, phosphorus, and organic matter availability needed for healthy plant growth. These findings are consistent with scientific research from other parts of Ethiopia (Bareke & Addi, 2020; Bareke et al., 2025; Gebru et al., 2016; Rehman et al., 2021; Ricigliano et al., 2025), which show that dust exposure harms livestock health by causing respiratory diseases such as bronchitis and pneumonia in cattle, while dust-covered vegetation lowers forage quality, reduces availability, and increases injury risk, affecting overall productivity.

Cultural and community impacts: the LULC analysis map has already shown that crushers alter landforms, vegetation, and water resources that hold cultural meaning, which are affected by constant noise, dust, and reduced environmental quality. The physical and psychological stress caused by noise, dust, and environmental degradation can reduce community participation in cultural events. The degradation of culturally significant bushland has weakened traditional connections to the landscape and threatened heritage. Combined with land loss, reduced natural resources, and occupational hazards, these impacts illustrate the broad spectrum of social risks linked to sand and

gravel production, emphasizing the intersection of environmental, health, and cultural concerns. Besides, the reduction of farmland over the last 20 years has negatively impacted the cultural heritage.

This is supported by the direct quotes of the interviewed farmers, who said:

> *"The reduction of our farmland as a result of crusher expansion has forced our children to take up wage labor to meet daily food needs. This is causing them to spend more time in these activities. Although they earn some income from the irregular local labour opportunities, traditional knowledge and practices have been declining each year."*

The findings also highlighted that manufactured sand and gravel production poses multiple social, environmental, and occupational challenges. Addressing these risks requires targeted mitigation measures, including sustainable land management, proper compensation mechanisms, dust and noise control, occupational safety interventions, and preservation of culturally significant sites. Integrating these measures would enhance community resilience, protect livelihoods, and minimize long-term socio-environmental impacts of sand and gravel operations.

Figure 4. 6: Untreated exposed part of the sand and gravel production sites: photo taken by the researcher, May, 2025

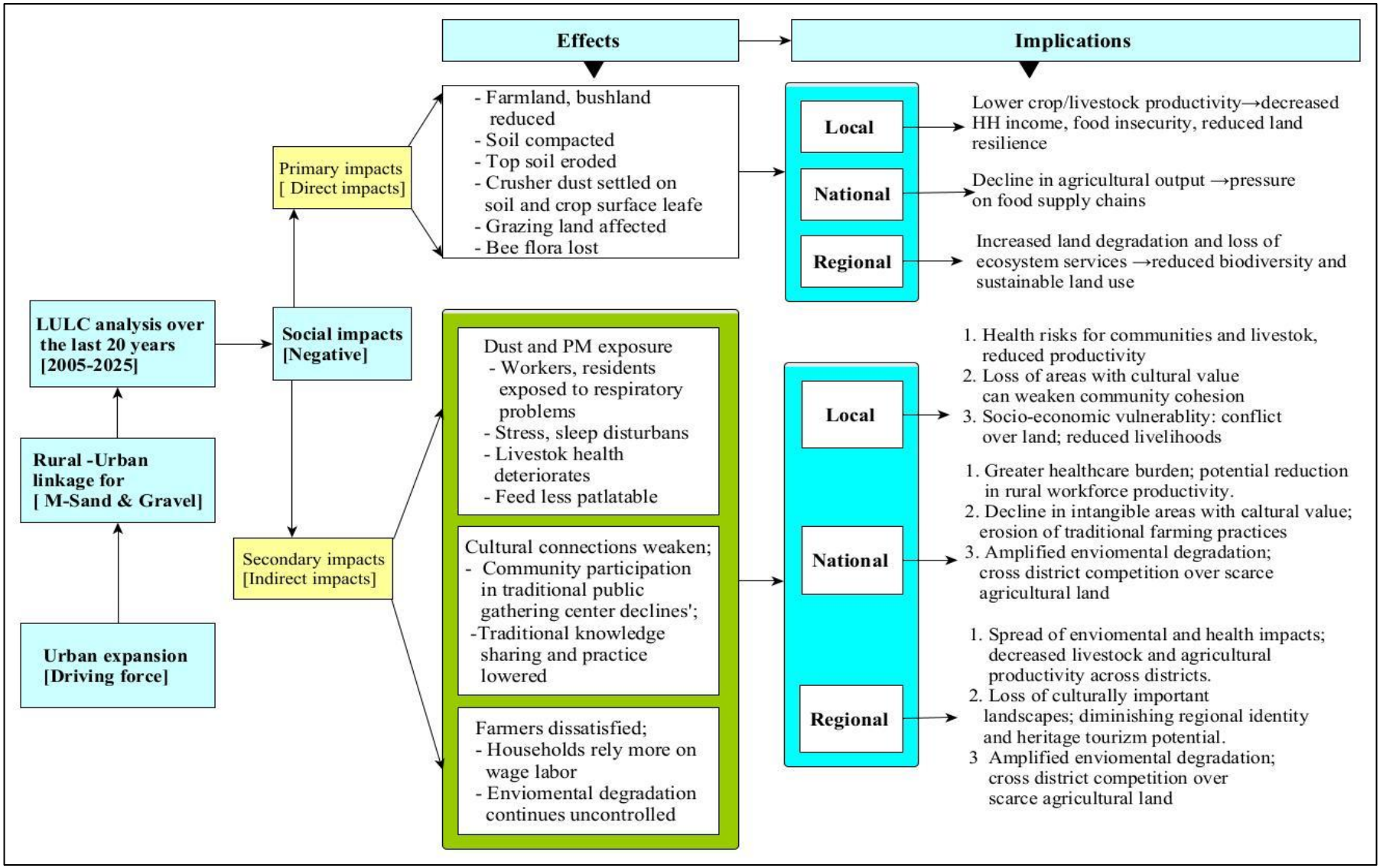


Figure 4. 7 Negative social impacts from the material flow and its implications

Source: Own conceptual understanding (2025)

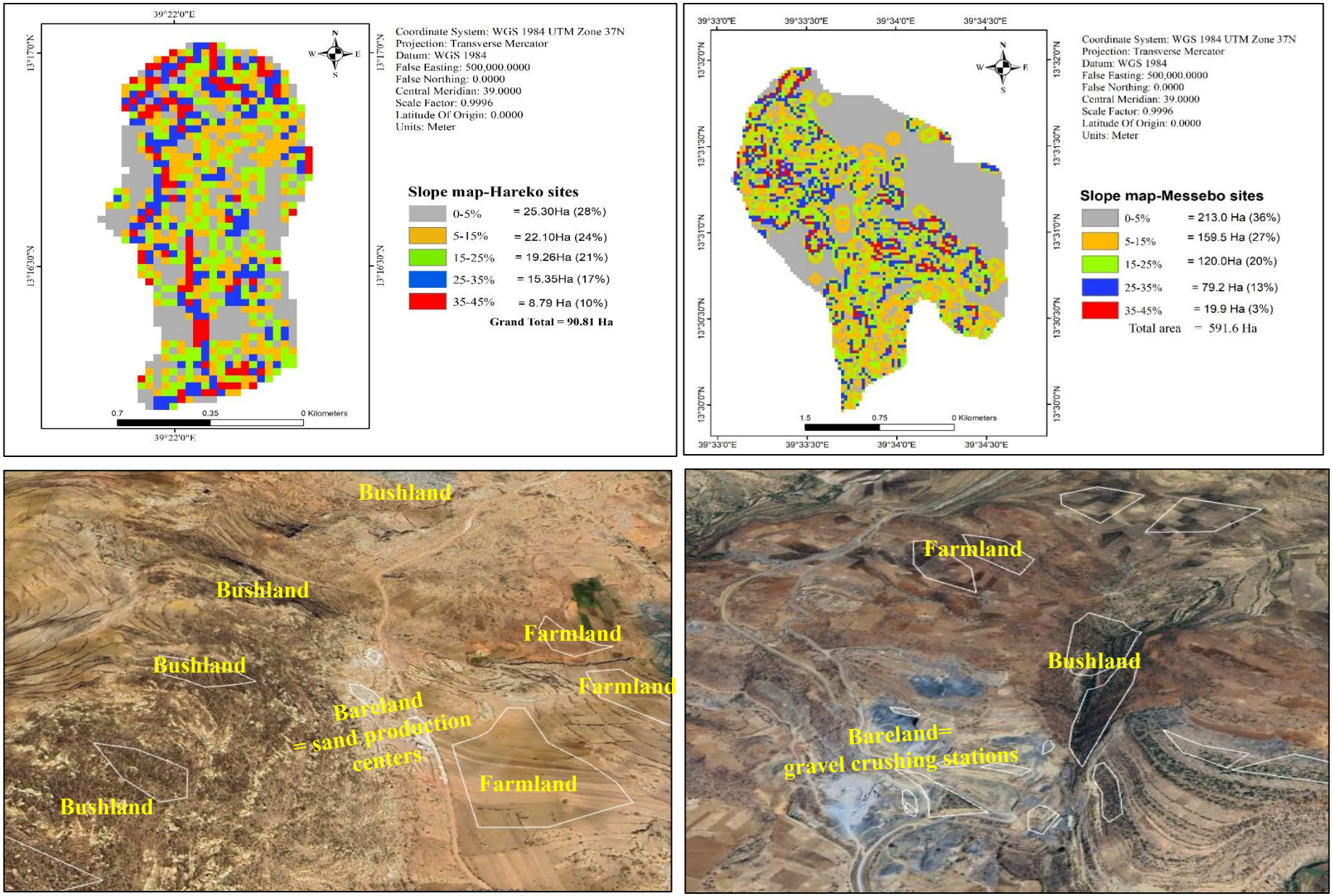


Figure 4. 8: Slope map of the study areas and their connection with ground

4.2.1.5 Environmental impacts of manufactured sand and gravel

4.2.1.5.1 Land use and land cover change

Over the past 20 years, the study area has experienced significant land use and land cover (LULC) changes due to sand and gravel extraction, with distinct impacts observed during two extraction phases: informal traditional-level extraction from 2005 to 2015 and formalized extraction using diesel and electric-powered crushers from 2015 to 2025. Field observations and focus group discussions with local respondents indicated that farmland and bushland were the most adversely affected land types, particularly during the formal extraction period, when intensified operations and crusher installations amplified environmental pressures.

To quantify these changes, a supervised classification using the maximum likelihood algorithm was conducted, categorizing the area into three primary classes: bare land, farmland, and bushland. Classified maps for the years 2005, 2015, and 2025 were generated and verified through ground-truthing to ensure accuracy. Analysis of these maps revealed that during the 2005–2015 period, farmland and bushland experienced moderate declines, reflecting the expansion of informal extraction activities, while bare land increased gradually due to surface disturbances. From 2015 to 2025, however, bare land expanded substantially as formal mining intensified, farmland declined markedly due to the loss and degradation of agricultural plots, and bushland was cleared for extraction pits, access roads, and crusher placement.

Table 4. 5: Change in land over the past 20 years in the Harerko and tabia Messobo -study areas

LULC types	Area in (Ha)-Hareko site			Area in (ha) Tabia Messebo site		
	2005	2015	2025	2005	2015	2025
Bare land (	1.98	4.13	17.91	6.01	19.89	361.835
Farm land	53.51	52.90	43.72	416.17	403.00	114.194
Bush land	35.40	33.62	28.96	169.83	168.91	115.421

Source: GIS and Remote sensing quantitative data analysis result, 2025

Land use types and area coverage in 2005: During this period, land use types remained relatively stable, as sand and gravel production through rock crushing did not expand significantly. Mining activities were mostly informal and illegal, relying on manual methods such as hammering rocks using locally available tools and materials. Production levels were very limited and primarily served

local construction needs at the village level, with occasional supply to small towns within the tabias. At this stage, farmland and bushland were not significantly or negatively affected by local mining activities, as indicated in the figure below.

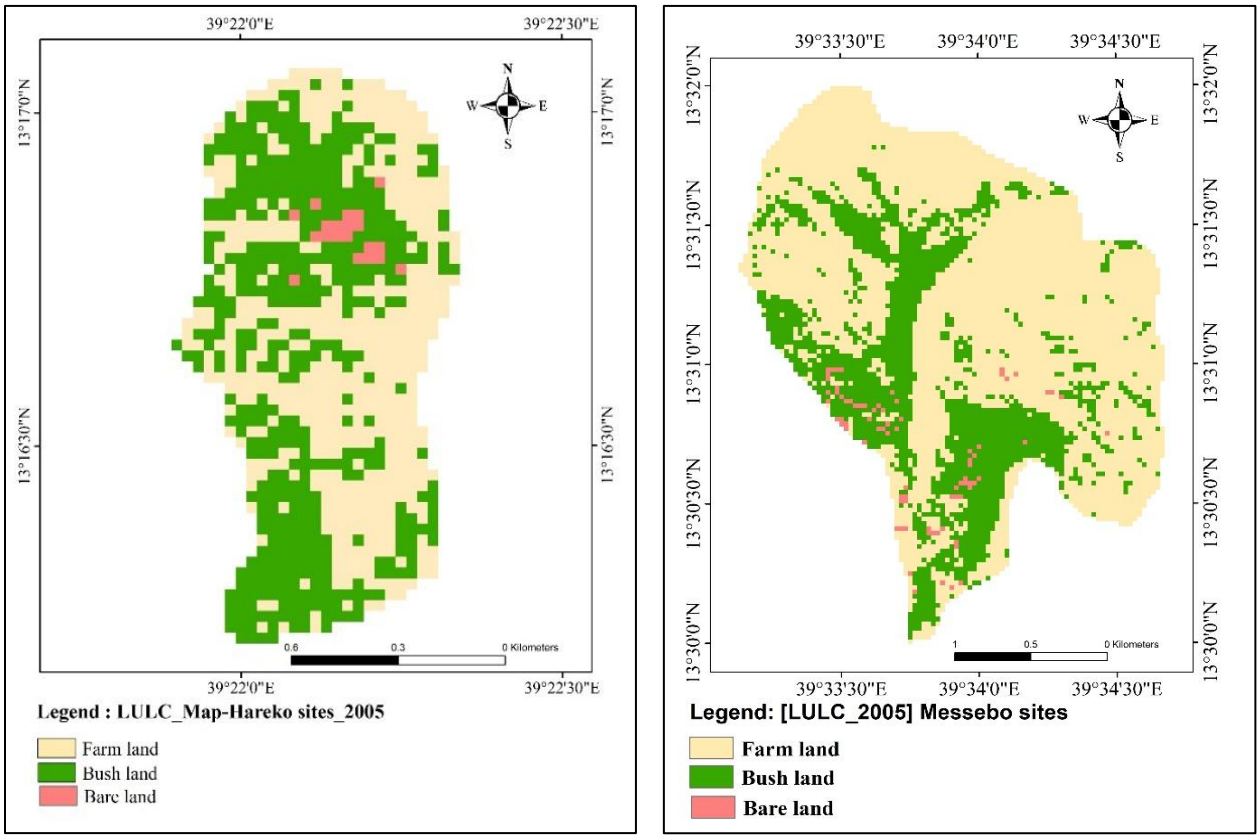


Figure 4. 9: Land use /land cover map of both study areas in 2005

Source: Study area analyzed maps using GIS and RS geospatial techniques, 2025

Change of rate 2005–2015: Within a 10-year interval, the bareland expansion for manufactured sand and gravel negatively affected the two land use types: farmland and bushland. The bareland, expanded due to the crusher's expansion, increased slightly from 1.98 ha to 4.13 ha, corresponding to a rate of change of 0.22 ha per year. As a result, farm land declined marginally from 53.51 ha to 52.90 ha (0.06 ha per year), and the bush land decreased from 35.40 ha to 33.62 ha (0.18 ha per year). While in the gravel production sites (in Tabia Messebo), bare land expanded from 6.01 ha to 19.89 ha at a rate of 1.39 ha per year. This also caused Farm land to decrease slightly from 416.17 ha to 403.00 ha (−1.32 ha per year), and bush land showed minimal decline from 169.83 ha to 168.91 ha (−0.09 ha per year

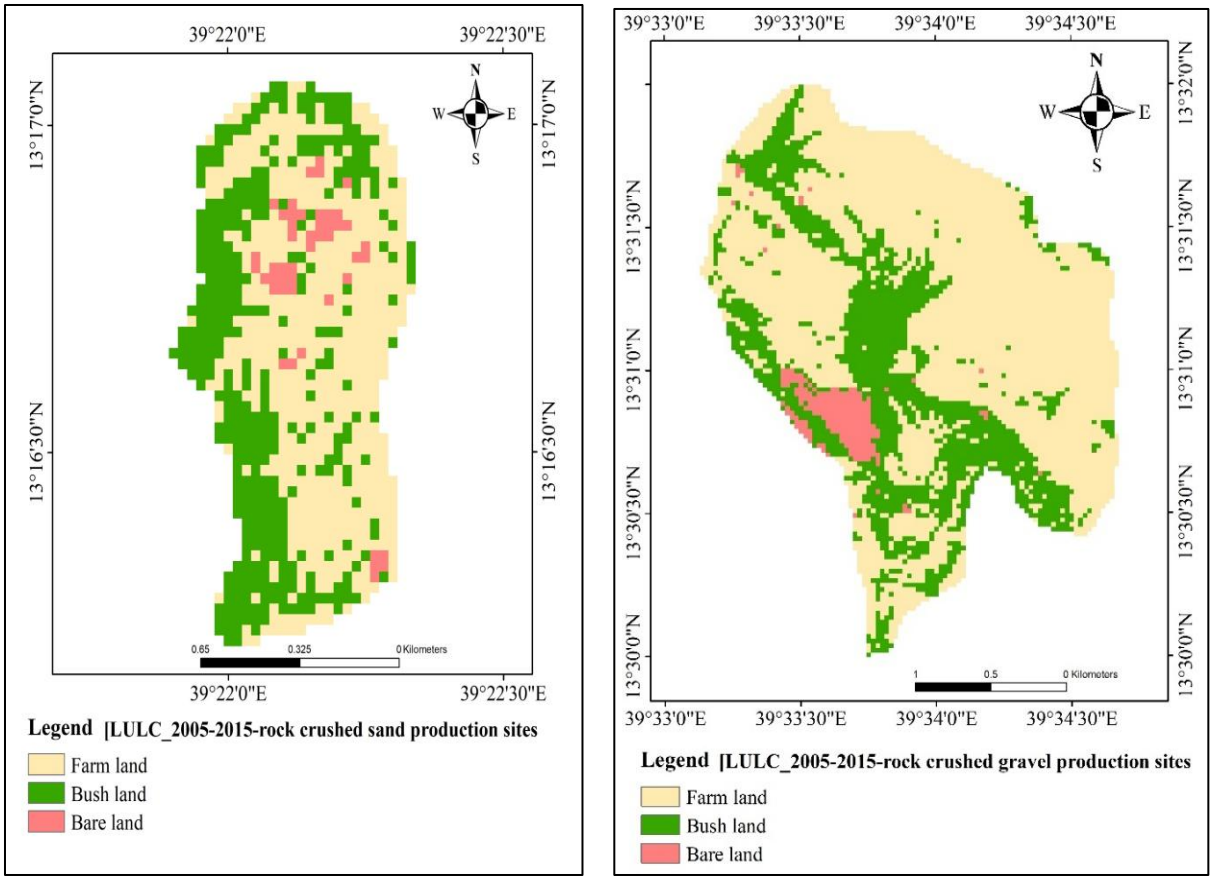


Figure 4. 10: Land use /land cover map of study areas (2005-2015)

Source: Study area analyzed maps using GIS and RS geospatial techniques, 2025

Change of rate 2015-2025: similarly, the analysis result indicated that in the last 10 years, continued the land use and land cover change due to continuous increment of bareland due to manufactured sand and gravel special increase from 4.13ha to 17.91ha corresponding to higher rate of 1.38ha per year in the manufactured sand production (hareko sites), and from 19.89ha to 161.84 ha at a an extremely high rate of 34.20 ha per year. The negative sign indicates the decline or reduction of the land use types due to bareland expansion over bushland and farmland for manufactured sand and gravel production.

Table 4. 6: Land use /land cover change rate of (2005-2015)

LULC type	Rate of the land use types change in the sand production sites (in Tabia Hareko)			Rate of land use type change in the Gravel production sites (in Tabia Messebo)		
	2005–2015	2015–2025	2005–2025	2005–2015	2015–2025	2005–2025
Bare land	+0.215	+1.378	+0.797	+1.388	+34.195	+17.791
Farm land	−0.061	−0.918	−0.490	−1.317	−28.881	−15.099
Bush land	−0.178	−0.466	−0.322	−0.092	−5.349	−2.720

Source: GIS/RS map outcomes quantitatively analyzed data, 2025

Change of rate 2005-2025: In the last 20 years, where manufactured sand and gravel production started, a significant land use change occurred in both study areas, though the difference and magnitude vary per site and period. The bareland significantly increased from 1.98 ha to 17.91 ha at a rate of 0.8ha per year in the Hareko site (manufactured sand production), while in messebo sites (manufactured gravel), production sites increased from 6.01ha in 2005 to 361ha in 2025, which is a great change, 17.8ha per year as detailed below.

Table 4. 7: Land use /land cover change rate of (2005-2025)

LULC type	Year		Rate of change (ha/yr)	Years		Rate of change (ha/yr)
	2005	2025		2005	2025	
Bare land	1.98	17.91	+0.8	6.01	361.84	+17.79
Farm land	53.51	43.72	−0.49	416.17	114.19	−15.10
Bush land	35.4	28.96	−0.32	169.83	115.42	−2.72

Source: GIS/RS map outcomes quantitatively analyzed data, 2025

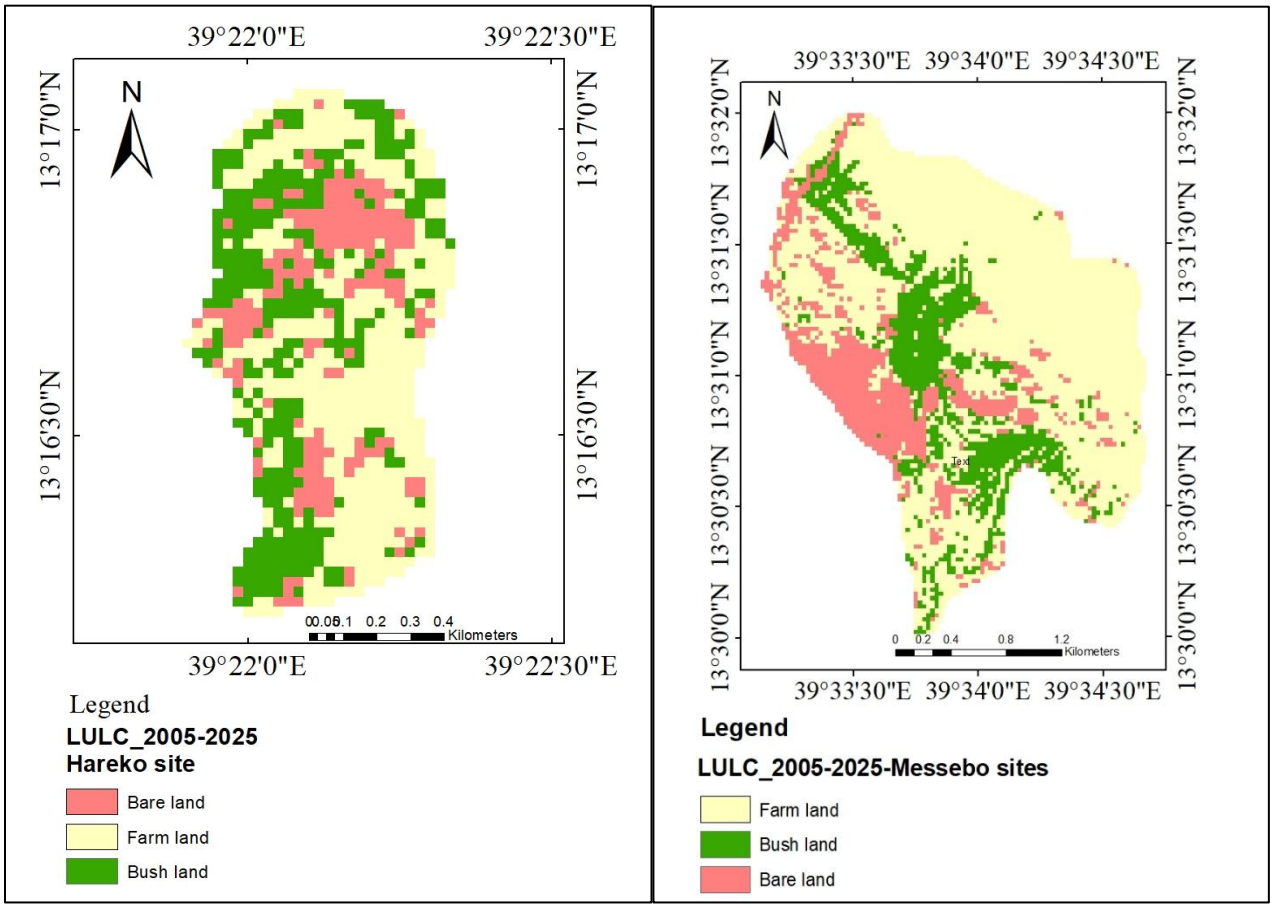


Figure 4. 11: Land use and land cover change due to manufactured sand and gravel expansion since 2005-2025

***Overall accuracy assessment of the LULC*:** Table 4.8 shows that the analysis shows that there is almost perfect agreement between the classification and reference data, with an overall accuracy of 95%. This accuracy is likely due to extensive ground truth verification and unique spectral signatures that make it easier to differentiate between categories. The results suggest that these land types have consistent features that reduce misclassification, which is important for accurate land use planning and resource management, also aligned with (Congalton and Rekas, 1985). The calculated overall accuracy assessment exceeds 96.8%, which is much greater than 80%, it signifies an excellent precision level in identifying land use and land cover that is in harmony with verified ground data (Abbas and Jaber, 2020). This high accuracy implies that an awesome majority of image pixels have been precisely classified according to their actual land cover types. Besides, a kappa value 93% indicates a remarkable harmony between the classified data and reference standards, pointing to an exacting classification process with scant likelihood of error. This is also consistent with the Kappa

statistic strength of agreement (Rwanga & Ndambuki, 2017), which is between 0.81 and 1 as highlighted in Table 3.4.

These measures are essential because they give policymakers and practitioners. Researchers' confidence in using the data for informed decisions, efficient and effective use, and management of construction material use under the framework of rural-urban linkage. The high accuracy levels and Kappa values confirm the reliability of remotely sensed data for assessing LULC impacts of manufactured sand and gravel expansion on farmland and bushland.

Table 4. 8: Accuracy assessment results/confusion matrix

Land use type (Category-A)	Reference data (A)				Row		
	Ref 1	Ref 2	Ref 3	Total	Error of confusion	Correct sampled	User accuracy
Farmland (Ref 1)	**24**	0	1	25	4%	24	96%
Bushland (Ref 2)	0	**19**	0	19	0%	19	100%
Bareland (Ref3)	1	0	**17**	18	6%	17	94%
Total	25	19	18	62		60	
Error of confusion	4%	0%	6%				
Producer accuracy	96.00%	100.00%	94.40%				
Overall classification accuracy		96.77%					
Random accuracy		35.19%					
Kappa coefficient (K)		95.02%					

Source: Analysis result, 2025

4.2.1.5.1.1 Land use and land cover change and its environmental implications

Over the past 20 years (2005–2025), sand and gravel mining has caused substantial transformations in land use and land cover (LULC), with impacts strongly influenced by slope gradients. The finding indicated that the gravel production sites, covering 591.6 ha, are distributed across slopes as follows: 36% on gentle slopes (0–5%), and 64% on moderately steep slopes (15–25%) to very steep slopes (35–45%). Similarly, the manufactured sand production sites (crushers), covering 90.81 ha, include 28% of the extraction on gentle slopes (0–10%), while 72% of the land occurs on moderate to very steep slopes. These slope ranges also aligned with the slope classification of (FAO, 2019), as shown

in the report shown by (Getachew & Meten, 2021). The slope distribution indicates that more than a third of gravel and nearly half of sand extraction occur on slopes exceeding 15–20%, identifying these areas as highly vulnerable to environmental degradation. GIS and remote sensing analyses reveal that the most intense land-use changes, including conversion of natural vegetation, dense bushland, and productive farmland into quarry pits, spoil disposal areas, access roads, and bare lands, occur predominantly on moderately steep to steep slopes (15–35%). Field observations and informant interviews confirm that slope-sensitive areas show accelerated erosion, landslide occurrence, and gully formation, highlighting the critical role of topography in environmental vulnerability. Based on this evidence, two primary and secondary environmental problems have resulted from the land use and land cover change as a result of the crusher expansions over the last 20 years, which also includes the impacts from the overall input -output process.

Primary (direct) impacts

***Soil and hydrological degradation*:** The growing removal of bushland over the last 20 years, combined with the absence of mitigation measures (section 4.1.3), has led to an increase in bareland that is highly susceptible to erosion. The study also indicated that dust generated from crushers has already settled on the soil, further changing its physical and chemical properties through the loss of organic matter and nutrients. This degradation negatively affects the growth of crops and vegetables also detailed under farmland size reduction and its implications. Also, these conditions can contribute to the reduction of the soil's water infiltration capacity, resulting in increased surface runoff and a severe decline in soil water availability, which is essential for agricultural production and plant growth.

The analyzed data collected from key informants at all levels showed common agreement (100%) that since the establishment of the crushers (2005-2005). This decline is mainly attributed to reduced soil fertility caused by off-site soil erosion impacts, such as sedimentation and contamination of farmland located on the downstream part of the crushers. Further scientific investigation is necessary to identify the specific types of contaminants present in sediments originating from the crushers and deposited on farmland. However, the accumulation of crushing dust on cropland is known to contain fine particulates that build up in the soil. This accumulation can increase elements such as carbonates, that led to higher soil alkalinity and reduced agricultural productivity.

The two key informants from Tabias's level agricultural staff, 100% noted the presence of ground-based signs that indicate these quarry residues can further fill natural water depressions, alter runoff patterns, and reduce soil elitist though clogging soil pores with fine particles. Combined with the fast expansion of quarry operations into farmland and bushland, these practices have led residents to report declines in livestock grazing and browsing areas.

Though the detail is presented under the current mitigation practices, the interviewed farmers about the soil degradation said that:

> *"The mountain above the sand crusher has long been respected for its ancestral and spiritual significance, which helped prevent deforestation. Now that it has been designated as the main raw material source, private operators have begun quarrying without sustainable measures, putting the site at risk. Farmers had warned of these dangers from the beginning, but their leaders dismissed their concerns."*

The findings also aligned with other related findings in Ethiopia and other areas (FAO, 2019; Sairanen & Rinne, 2019; Torres et al., 2017; Gashaw &Aklilu, 2020; Getachew & Meten, 2021; Meaux et al., 2022; Han et al., 2023; Elnourani et al., 2024) they reported that growing construction demand drives unregulated extraction activities that remove bushland and disturb soil, causing erosion particularly in extraction in slope area, alter soil infiltration capacity from dust and poor space clogging effect, soil and water contamination, and loss of soil fertility, which ultimately leads to land degradation and reduced agricultural productivity.

***Vegetation and biodiversity loss*:** As evidenced by the LULC over the last 20 years**,** vegetation clearance on slopes above 15% has caused substantial ecological disruption. Dense bushland and native flora, which historically stabilized soils, have been removed, leading to increased erosion, and can lead to reduced soil moisture retention and fragmentation of habitats. Key honey-producing species, including *Becium grandiflorum*, *Hypoestes forskaolii*, and *Leucas abyssinica,* have been lost from steep hillsides, contributing to measurable declines in honey production and pollination efficiency. Wildlife corridors for species such as hyenas, rabbits, and foxes are disrupted, with the greatest impacts observed on slopes above 25%. The removal of vegetation has also diminished natural soil stabilization, further compounding slope-dependent erosion and sediment transport. Informants at Messobo reported that decades of bushland and tree removal for fuelwood and gravel mining led to extensive soil exposure and farmland at risk of sedimentation, illustrating the cumulative effect of slope-sensitive vegetation loss. Besides, the study highlighted that the increasing

bushland removal over the last 20 years, integrated with the dust, can increase the local surface temperatures and reduce humidity, stressing vegetables that require stable and temperature conditions. These findings also aligned with other related findings in Ethiopia and other areas (Zhao et al., 2025; Mariye et al., 2024; Rehman et al., 2021; Gebru et al., 2016), showing that manufactured sand and gravel reduce bushland, shrubland, and vegetation productivity, though impairing photosynthesis, lowering forage quality for livestock, increasing local temperature, reducing soil water infiltration capacity, collectively contributing to vegetation loss and ecosystem deterioration.

Visual effect: Site-level observations indicated that damage to the landscape is one of the major environmental problems at both sites. Respondents reported that during the rainy season, open pits from the sand and gravel mining and open dumping areas collect water, forming unsightly spoil heaps and barren wildernesses that disrupt the natural visual character of the villages. The analysis also highlighted significant challenges related to weak overburden and by-product management. Overburden, fines, and rejected materials were disposed of along roadsides bordering farmland and bushland, increasing the risks of soil degradation, water contamination, and negatively impacting the amenity of the local environment.

The four woreda-level environmental and natural resource staff 100% warned that the lack of a sustainable waste management framework, together with growing quarry demand and rising by-products volume, is likely to worsen environmental risk like damage to the natural sustainability of the environment in the coming years. They emphasized that without regulated dumping sites, enforced quarry rehabilitation, and soil and water conservation measures, the natural amenity of the environment, the local ecosystem in general, could face severe and potentially irreversible ecological and socio-economic damage. Besides the interviewed participants and site-level observation, there were highly visible scars, deep pits, and unstable spoil heaps, as well as improperly disposed of overburden along roads, significantly changing the natural amenity of the sites.

Besides, the GIS/remote sensing analyzed slope map shows that slopes between 25–35% and 35–45% exhibited the most pronounced visual and environmental impacts, including exposed bare surfaces and altered drainage patterns. Also, 5% of interviewed farmers emphasized that upstream sedimentary rock areas were culturally and spiritually significant, and sand extraction threatened these traditional connections. This finding indicates that these disturbances not only reduce ecosystem stability but also degrade aesthetic quality, demonstrating the compounded effect of slope on visual and landscape integrity. Similar research results were also presented on Ethiopia and different areas

(Gebru et al., 2025; Sultan et al., 2025; Muriki et al., 2024; Forster et al., 2021; Chuvieco, 2020; Desa, 2019), showing that manufactured sand and gravel extraction degrade ecosystems and visibly alter landscapes, leading to the loss of scenic and aesthetic value of the environment and local ecosystem.

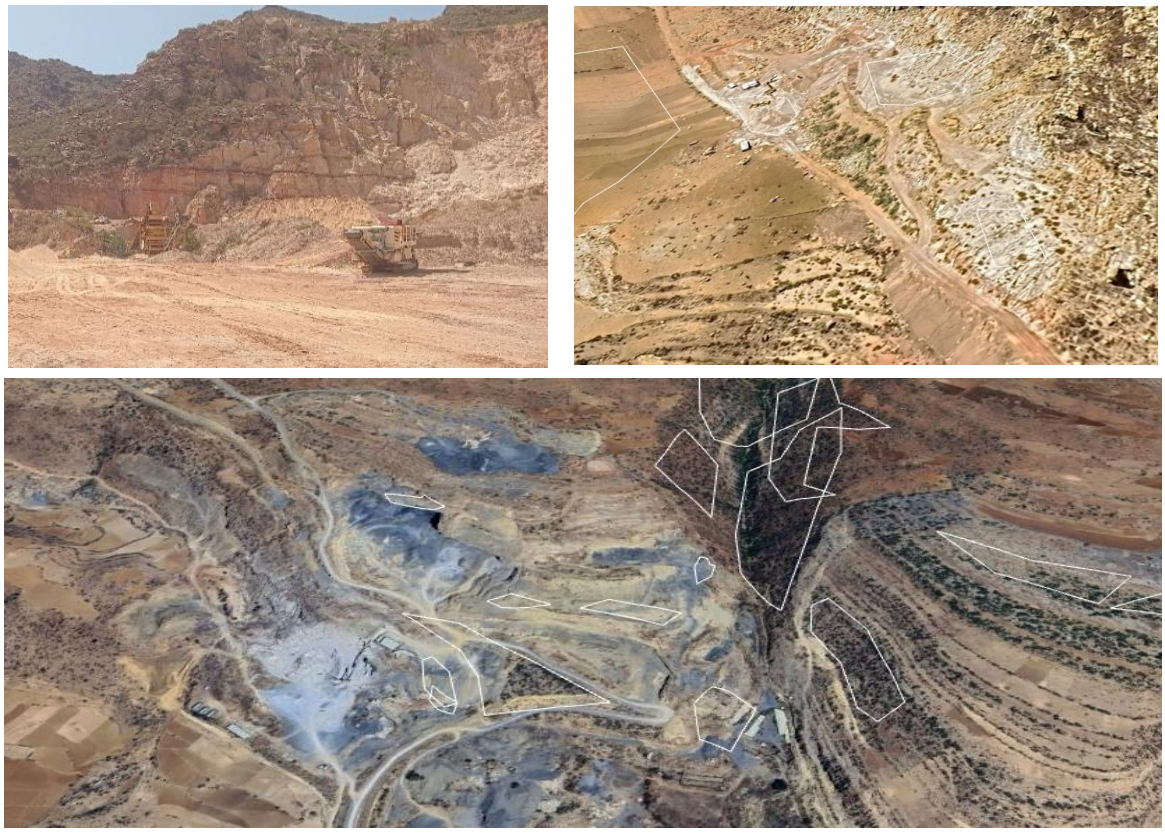


Figure 4. 12: The topographical situation of the production sites and their implication land degradation: Photo taken by the researcher in April 2025

A) Secondary (Indirect) Impacts

Air and sound/noise pollution: Air and noise pollution were the major findings across the study areas. All surveyed respondents (100%) stated that persistent emissions and noise from the crushers, particularly during the day, become very serious, mainly for those who live close to the crushers. This was also highlighted by the two environmental officers interviewed at the woreda level. They explained that though homes are almost 500 meters away from the crushers (the recommended standard as per the national EPA document), unmeasured noise from the crushers prevents children and babies from sleeping well during the day and night.

Site-level observations also confirmed that daily human activities near crusher sites and livestock grazing on dust-coated vegetation further exacerbate the direct and indirect impacts of air and noise pollution. Plant leaves were observed to be heavily coated with dust particles and to have changed color, which can affect their growth and production by altering the natural photosynthesis process. Besides, the two interviewed woreda-level forestry experts said that:

> "*Dust clogs the intercellular openings (stomata) of lower leaves, impairing plant respiration and tree health, as explained."*

The site-level observation was also supported by the dust emission indicated in Figure 4.5, showing that dust and noise effects were more intensified on the sloped parts of these sites. As per the surveyed respondents' response (100%), this was due to the topography facilitating downhill propagation, thereby amplifying the indirect impacts of mining on ecosystem services and agricultural productivity. These findings are also aligned with a recent study conducted in Ethiopia (Saleem & Ayalew, 2025), which found that operations producing manufactured sand and gravel generate significant air pollution, dust, and noise, reflecting persistent environmental concerns arising from mining activities.

Climate and micro-climate changes: This was another environmental consequence of the manufactured sand and gravel mining study areas produced using electricity and diesel-powered crushers. The major climate and microclimate changes were identified both qualitatively and quantitatively from two main sources: carbon emission from energy consumption at production sites, and from bushland that includes vegetation reduction over the last 20 years.

Carbon emissions*:* the two main sources of energy for the manufacturing of sand and gravel crushers were diesel and electricity. The total annual diesel consumption of the crushers was 150,173 liters under the cradle-to-grave system boundary. From this, approximately 397,958.45 kg CO_2e per year was estimated based on a contextualized emission factor of 2.65 kg CO_2e per liter. Similarly, the annual electricity consumption of the crushers was found to be 210 kWh per motor over 1,760 working hours per year. Using Ethiopia's national grid emission factor of 0.0164 kg CO_2e per kWh, this translates to an annual emission of approximately 6,061 kg CO_2e (6.06 tCO_2e) per motor. Combining both energy sources, a total of 404,021.94 kg CO_2e per year, equivalent to 2.23 kg CO_2e per ton, was estimated, with implications at both local and national levels.

Local and international level comparison and constructs of the carbon emission (combined result): This combined result indicated that manufacturing sand and gravel is contributing significantly to the local industrial emissions, particularly in the regions where energy-intensive mining activities are concentrated. Diesel remains a dominant emission source, reflecting reliance on fossil duels, while electricity contributes a smaller share sue to Ethiopia's low -carbon hydropower -dominated grid. At the local scale, these emissions have direct implications for air quality, climate mitigation efforts, and alignment with Ethiopia's national environmental goals, such as reducing fossil fuel dependency in industrial sectors.

However, site managers, drivers, and crusher operators reported that electric-powered crushers still use some fossil fuel for backup, which produces carbon dioxide and other greenhouse gases, contributing to regional and global warming. When compared to international sand and gravel production, the emission level of 2.23 kg CO_2e per ton is relatively low. These findings are consistent with other studies (Peppas et al., 2025; LCP, 2023), which show that Ethiopia's hydropower-based grid has very low emissions, while diesel-powered industrial equipment remains a major source of CO_2 and environmental damage. Both locally and globally, diesel combustion is the primary emission source, whereas electricity contributes less due to grid characteristics. This indicates that diesel remains the main driver of local emissions, highlighting opportunities for cleaner energy integration to meet national and international climate objectives. Therefore, the findings illustrated that the dual role of local energy mix in limiting per-ton emissions, while also posing the persistent challenge of fossil fuel use. In this case, the study indicated the following key trends:

- ***Sign of local air warming****:* About 55% of the sampled farmer respondents reported that, following the installation of the crushers, there has been a significant change in local climatic conditions, particularly for those living near the crushers. Similarly, woreda-level forestry and natural resource experts suggested that these changes could be attributed to broader climate change or the unmanaged destruction of bushland for extraction purposes. Elder farmers who were interviewed also shared similar long-term observations. These notes that while the climatic changes are often mild, periods of calm wind are associated with unusual warming near the crushers, conditions that were uncommon in the past.

  Discussion with crusher operators and drivers further indicated that diesel-powered crushers, especially stationary units and haulage equipment, generate substantial waste heat during operation. These observations align with findings from the LUCL analysis maps, which indicate

increasing bushland destruction and expansion of bare land over the past 20 years. Although other external factors, such as global climate change, may also contribute to the observed warming, further research is required to quantify their contributions. All the sampled farmers, experts, and site managers identified diesel-powered crushers used for manufactured sand and gravel production as a key contributor to greenhouse gas emissions. Therefore, continued dependence on diesel could contribute to rising near -surface temperature around production sites.

These trends are further supported by the significant expansion of production areas over the past two decades, accompanied by a marked decline in bushland cover, which reduces carbon sequestration capacity ad increase land surface exposure.

- ***Contribution to regional climate driving***: Although the calculated dual carbon emission of 2.23 kg CO_2 per ton is relatively small for the reasons stated, it still contributes to GHG-driven warming. This effect is expected to worsen in the coming periods if dependency on diesel -powered crushers continues and crushing sites accumulate energy balance. These findings suggest that diesel use in crushing operations can intensify microclimate warming through a combination of direct heat emissions, GHGs, and surface changes, producing localized heat stress and cumulatively contributing to broader regional climate alteration. changes, producing localized heat as per the stated reasons, which can be attributed to greenhouse gas driving. This is also expected to be worsened in the next periods when the dependency on the diesel-powered crushers continues, and crushing sites accumulate across a region, they enhance regional warming trends and modify the atmospheric energy balance. These findings imply that diesel dependency across crushing operations can intensify microclimate warming through combining direct heat emissions, greenhouse gases, and land surface changes. It can produce localized heat stress and contribute cumulatively to broader regional climate alteration. The results align with previous research (Vural et al.,2025; Swift et al., 2023), indicating that diesel-powered sand and gravel production releases substantial heat and greenhouse gases and alters land surfaces, thereby increasing local warming and heat stress s and contributing to broader regional climate change.

Bushland reduction and its implications for carbon emissions: The study did not provide a full quantification of carbon sequestered by soil, bushland, and grasses, as many factors can influence sequestration, including the baseline extent of bushland before disturbance. Accordingly, the analysis relied primarily on the LULC map results. The reduction in bushland over the past 20 years may decrease carbon sequestration, thereby weakening local and national greenhouse gas mitigation

efforts. Reduced vegetation cover can accelerate regional and global warming by diminishing the natural cooling effects provided by healthy ecosystems.

Disruption of local water cycles through reduced transpiration may lower atmospheric moisture, cloud formation, and rainfall, leading to drier microclimatic conditions and increased drought risk. Alterations in watershed surface characteristics, such as roughness and moisture resulting from vegetation loss, can also affect energy exchange between the land and the atmosphere, further disrupting the local energy balance. Besides, the expansion of extraction activities has increased bareland areas, which absorb more heat, raise local temperatures, and potentially influence regional rainfall patterns. These findings are also consistent with other scientific research studies conducted in Ethiopia (Belay et al., 2025; Bikeko &E, 2024; Gitima et al., 2025), which show that the expansion of sand and gravel manufacturing has led to bushland reduction, decreased carbon storage, disturbed water cycles and local climate, increased surface temperature, reduced moisture levels, and altered rainfall patterns through changes in evapotranspiration.

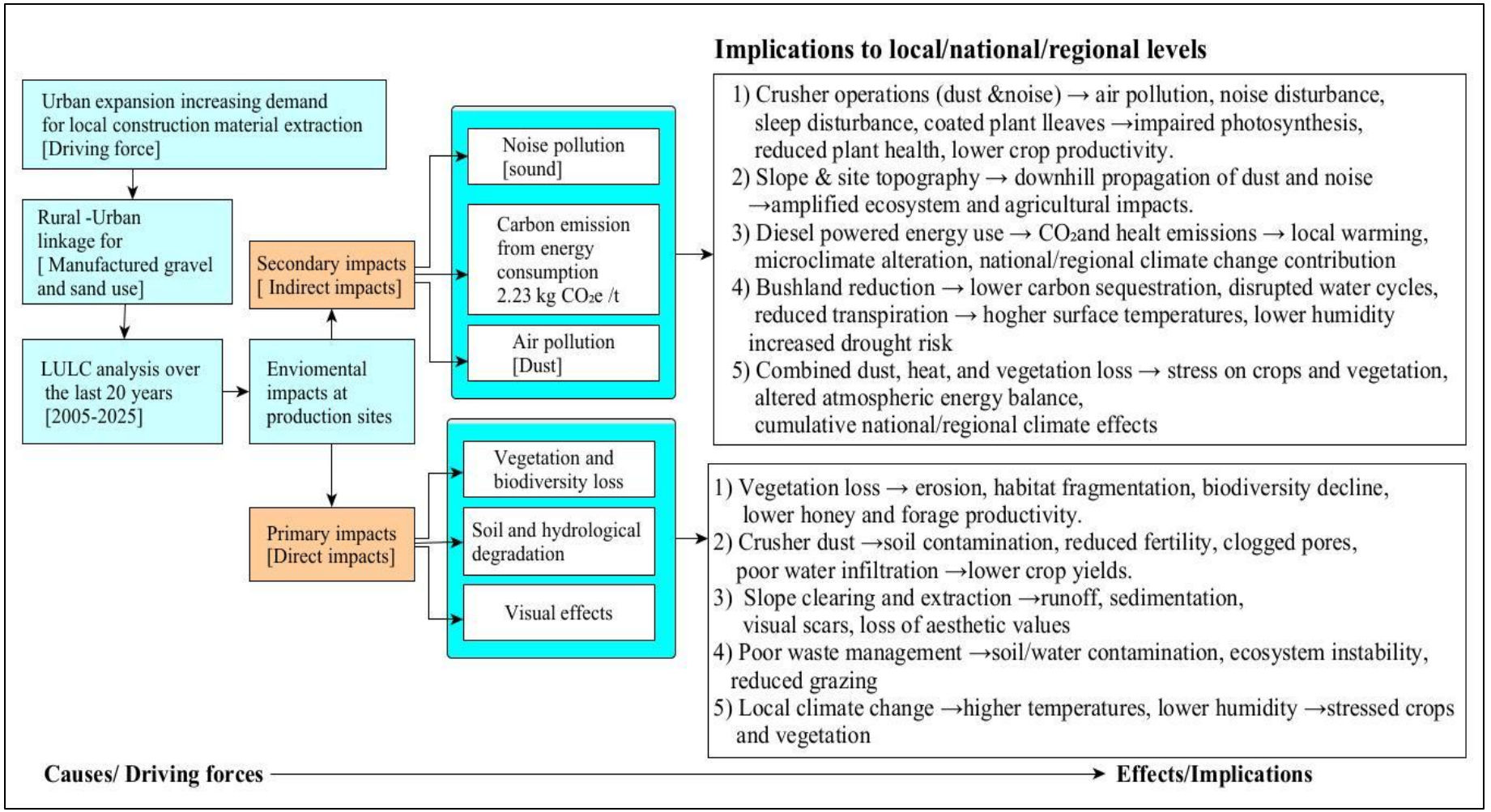


Figure 4. 13: Environmental impacts from the material flow and their implication to local and national levels

Source: Own conceptual understanding (2025)

4.1.3 Current mitigation practices

As detailed in section 2.2.6 (Conceptual Framework), the study assessed both social and environmental mitigation measures currently implemented across the study areas to address the negative impacts of extraction.

4.1.3.1 Policy framework and practices

Understanding the national level environmental policy (1997) and the constitution (1997) as overarching frameworks, key federal laws, proclamations, and supporting guidelines were reviewed. These include:

1. Federal laws and proclamation which include the Environmental and Social Impact Assessment Proclamation No.1371/2025 and the Environmental Pollution Control Proclamation No.300/2002.
2. Public Health and Workspace Safety Measures. Including public health proclamation No.200/2000, labour proclamation No. 377/2003 with occupational safety and health provisions, and the Ethiopian Occupational Safety and Health Directive.
3. Environmental and Air Quality Standards, such as the Ambient Environmental Standards of Ethiopia, serve to interpret Proclamation No.300/2000.
4. Health and Environmental Intersection Resources, including the UNDP-EPA Legal Environmental Assessment for Air Pollution and Health.

All the documents, the constitution, and supporting guidelines, encourage the adoption of sustainable operational practices and meaningful community engagement, consistent with findings of (EEPA,2005) and (Saleem & Ayalew, 2025).

After reviewing these documents, a discussion was held with environmental protection staff regarding their familiarity with and access to them. The findings indicate that, while staff members are theoretically aware of the documents, they lack detailed practical knowledge and a comprehensive understanding of the stated guidelines, policies, and proclamations. This gap appears to result from a lack of demand -driven training, limited emphasis on policy and proclamation implementation by higher-level authorities, and insufficient budget allocation for implementation.

These findings indicate that, despite the existence of relevant national policies and proclamations, mainly available at the main office level, their effective implementation was found to be very weak. The absence of printed and well-documented guidelines with detailed implementation procedures,

restricted access to official documents, particularly at the site level, and reliance on existing agreement templates without updates transferred from one project investor to another reflect gaps between policy provisions and actual practice. The template, which lacks updates for agreements required crusher investors to conduct an environmental impact assessment with detailed and budgeted appropriate mitigation measures for each of the identified negative impacts. However, the lack of accessible official manuals, comprehensive dissemination, consistent institutional follow-up, and effective enforcement clearly demonstrates that environmental policies and proclamations were weakly and inadequately implemented across all study areas.

As an integral part of this policy framework and practices, the agreement document signed with the study area investors (seven crusher owners) was reviewed with the support of a formal university consent letter indicating the purpose of the data collected and requests. The agreements were found to be almost consistent with the requirements stated in the policy and proclamations; however, they lacked sufficient detail. The signed agreement documents lacked validation of the proposed mitigation measures, assessment of their consistency with the identified environmental and social impacts, evidence of community acceptance, and inclusion of community perspectives. Accordingly, during the implementation process, significant complaints were raised by the community; however, these grievances were not formally addressed or documented. Implementation proceeded with the support of woreda authorities to avoid disruption of project activities, while emphasizing that payment for leased private land would be provided in accordance with the provisions.

These results indicate that, although the policies are well formulated on paper, their implementation was found very weak due to key shortcomings identified and prioritized by research survey participants, who totally agreed (100%). These weaknesses include:

1. Lack of community participation throughout the process, from site selection to documentation, where decisions were made primarily by higher-level leaders and a few tabia-level representatives.
2. Absence of awareness-raising activities on policy requirements for either the community or their representatives, with most matters handled by a small group of woreda officials.
3. Weak support from tabia and woreda staff, with delayed response to appeals and complaints being a persistent problem.
4. Limited monitoring and evaluation from woreda or regional level staff, particularly from land protection and mining authorities.

These gaps allowed crusher owners to bypass agreed mitigation measures, even where such measures were specified but lacked detail. These findings aligned with previously identified bottlenecks for environmental policy implementation in Ethiopia (Andualm et al., 2025; FERA,2022; Kassa et al., 2017; Mitike et al.,2016) which include: 1) weak institutional capacity, 2) poor integration of quarry site management into local lan-use planning, leading to governance gaps between customary land tenure systems and formal regulations, 3) weak coordination among government stakeholders due to fragmented responsibilities across ministries, undermines joint planning and effective action, and 4) limited enforcement of occupational health standards and widespread biomass fuel use, contributing significantly to air pollution. Moreover, the revised documents highlight key gaps that align with the findings, like a lack of a concrete policy implementation action plan, and the absence of contextualized standards. For example, for the Ambient Environmental Standards of Ethiopia, there are gaps that the policy itself identifies as next steps for regional authorities. Generally, the results suggest that the environmental protection policy and proclamations are well-prepared in design but stunted in implementation. It lacks a strong connection to on-the-ground practice, including close monitoring and evaluation of planned mitigation measures and their effectiveness in addressing the environmental and social impacts of manufactured sand and gravel production. This gap requires urgent attention from top-level policymakers and planners.

4.1.3.2 Environmental mitigation measure

There are planned mitigation measures to address the environmental impacts of manufactured sand and gravel extraction, as detailed in Figure 4.8. The mitigation measures identified from the agreement document review include slope stabilization and revegetation, vegetation buffering and land rehabilitation, by-product recycling /reuse, dust control through water spraying, energy-efficient or optimized use of electricity-powered crushers, integrated sustainable practices, and close monitoring and enforcement by the regulatory body. However, the implementation of these planned mitigation measures is largely absent, with the exception of dust control, which is partially applied through water spraying during operations.

Crusher dust control through water spraying*:* This activity was the prime mitigation measure currently practiced across the study areas. According to data collected using the LCI method from secondary sources, a total of 21,596 m^3 of water per annum was utilized. The water was utilized to control 492.41 kg/year (0.492 t/year) of dust generated by all seven crushers. This represents the amount of dust emitted under uncontrolled conditions. After applying the water, annual dust emissions

were reduced to 148 kg/year (0.148 t/year), achieving an average reduction efficiency of 70%, equivalent to 0.345 t/year of dust avoided. This demonstrates that water spraying is technically effective when properly applied and is also important in reducing airborne diseases and improving air quality. This achievement falls within the 40-80% efficiency range reported for wet dust suppression systems (EPA,2006), confirming consistency with internationally recognized performance benchmarks.

However, limitations were observed, including irregular application, reliance on large and unregulated water use, and limited attention to long-term impacts on local surface and groundwater. Dust suppression relies heavily on unregulated abstraction of surface and groundwater without any alternative practices, raising significant concerns about local water sustainability. Investors extract a large volume of water from surrounding areas, primarily around Adigudom town and other parts of the Enderata districts, without providing compensation or payment to the local community. They lack water-harvesting technologies, particularly rainwater harvesting, and do not employ alternatives beyond extracting locally available surface and groundwater. Groundwater was also extracted for other operational purposes without restriction, which can result in additional environmental and social impacts. These findings are consistent with studies from other parts of Ethiopia (Ahmed, 2023), showing that the free extraction of water for crusher purposes frequently generates social complaints and concerns over aquifer depletion. This trend may shift environmental pressures from air quality to water resources and is expected to worsen in the future unless sustained measures are implemented. This situation is also expected to worsen in the future if sustained measures, mainly regulatory response and requirements for investors to secure alternative water sources, are not implemented. This indicates that planned environmental mitigation measures were not carried out due to the following main reasons: 1) weak compliance, including disrupted monitoring, absence of structured plans for by-product management, and lack of policy enforcement. 2) Limited rehabilitation efforts, such as vegetation buffering and land restoration, due to prioritization of immediate profit over environmental sustainability. 3) Limited technical and institutional capacity, which hindered the adoption of energy-efficient machinery and renewable energy solutions. Accordingly, key recommended measures include regulatory enforcement and requiring investors to develop alternative water sources, such as surface water harvesting, underground water storage tanks, or advanced dust monitoring technologies.

4.3.2 Socio-economic mitigation measures and effectiveness

Socio-economic mitigation measures (Annex VII) at the sand and gravel extraction sites were largely inconsistent and insufficient, limiting their effectiveness in offsetting the negative impacts of quarry operations. Although investor agreements included provisions for farmland compensation or payment for leased land, fertilizer support, infrastructure development, and health and welfare programs, implementation was uneven and often inadequate. For instance, payment for 10 hectares of farmland, collectively owned by 29 farmers, was provided under the investor agreements, totaling 12,083,333 Birr, with individual payments averaging 96,667 Birr, depending on the land area owned by each farmer. To date, only 87% of the farmers have received the payment, while the remaining 13% have not, due to pending documentation and approval processes. Although the payments provided short-term financial relief, they did not reflect the long-term economic value of the land or address lost employment opportunities tied to farming activities. Appeals submitted by affected farmers through local administrations were largely unaddressed. Which is further exacerbating livelihood insecurity and undermining trust in both investors and authorities. Participants from Hareko sites said that:

> "The *payment given for the leased farmland did not align with the current purchasing power parity of the birr, both in the local and national markets. This benefits private investors at the expense of the poor and the environment. However, we still trust that the respective woreda, zonal, and regional bodies will consider our appeal and come up with a sustainable solution."*

Moreover, in Hintal Woreda, communally owned land previously cultivated by youth groups was leased to a private investor without community consultation. This is integrated with the dust emission impacts on crop land close to the production centers, creating unresolved disputes and escalating social tensions as production began. As an immediate solution, fertilizer support was provided to six farmers severely affected by dust emissions, delivering 50 kg per person per year to partially compensate for declining crop productivity. While this provided short-term relief, ongoing dust deposition and land degradation limited its effectiveness, consistent with studies showing that mining dust disrupts soil nutrient cycles, depletes key nutrients, increases compaction, and reduces crop yields (Belay et al., 2020; Hemmler et al., 2024; Zhao et al., 2025). Similarly, the farmers emphasized that although these measures mitigated immediate economic stress, the structural decline in soil fertility remained unaddressed, threatening long-term productivity.

Infrastructure development was minimal, with only one investor at Hareko sites, where a church was constructed and financed, and electricity was installed. This strengthened social cohesion and improved community access to religious services. Besides, health and welfare support required each crusher to contribute >200,000 Birr/year for vulnerable households. Of seven crushers, only four (57%) participated, and the support was insufficient. Communities reported limited responsiveness from local authorities when grievances were raised, further weakening trust. Low compliance reflected weak monitoring, irregular follow-up, and limited accountability. Collectively, these findings demonstrate that social mitigation measures were fragmented and inconsistently applied, providing limited short-term relief without ensuring long-term resilience. The research further highlights that the combined lack of consistent compensation, fertilizer support, infrastructure investment, and health programs, alongside unaddressed environmental degradation, amplified social vulnerability. This implies that the investors focused primarily on profit, paying little attention to social obligations.

Integrating socio-economic measures with environmental rehabilitation, dust mitigation, and participatory management could strengthen community trust, sustain livelihoods, extend employment beyond extraction phases, and enhance overall resilience. This is also consistent with evidence from national land restoration initiatives in Ethiopia, which shows that participatory approaches in nursery management, seedling production, and rehabilitation work can improve both ecosystem services and rural livelihoods (Abera, 2020; Saleem & Ayalew, 2025; Weldeamanuel & Cheng, 2024). The absence of such integrated practices at the study sites represents both a socio-economic and environmental failure, constraining the sustainability of sand and gravel production.

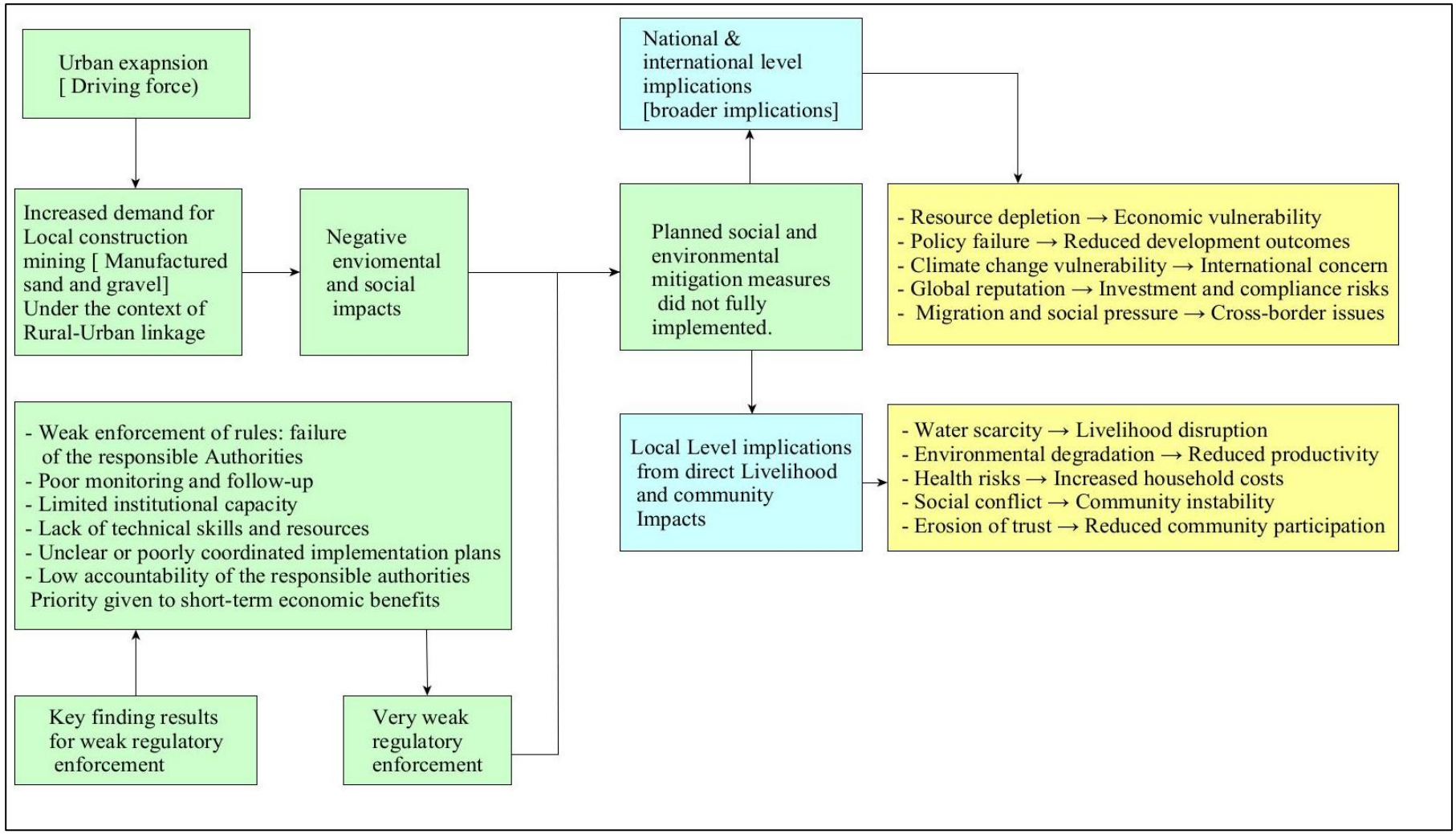


Figure 4. 14: Socio-environmental negative impacts from the material flow and their implication to local/ national and regional levels

Source: Own conceptual understanding (2025)

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The study analyzed the impact of urban-rural linkages on construction material flow in Mekelle and the surrounding rural areas. Using a mixed-methods approach, the study adopted a cradle-to-gate-system boundary under the umbrella of cradle-to-Gravel concept due to data inconsistency. The findings show that a total of 86,680 m^3 of manufactured sand and gravel is produced per annum, of which 15% dumped as byproduct. A total of 159 rural and urban dwellers benefit from this material flow through daily labour, driving, and income from trading the manufactured materials. Despite these challenges, manufacturing sand and gravel remains an untapped potential for supplying construction materials to support rapid urban expansion and meet the growing local demand. The supply system also represents a significant opportunity for job creation, particularly for landless and unemployed youth in Tigray and across Ethiopia. This directly and indirectly contributes to both local and national economic development

However, significant environmental and social problems are emerging as serious problems across the study areas. Geospatial analysis showed that the bare land resulting from the rapid expansion of crushers has led to a significant decrease in farm and bushland over the last 20 years, causing direct and indirect impacts such as land degradation and air pollution. In addition, 2.23 kg of carbon dioxide equivalent emission per ton, raising concerns at both the local and national levels regarding climate change. The primary reasons for these socio-environmental impacts are weak regulatory enforcement, which has allowed investors to neglect the implementation of at least planned mitigation measures. Thus, the extraction of these resources should be conducted in consultation with local communities, with close follow-up and evaluation by regulatory authorities to track the implementation and effectiveness of planned mitigation measures in addressing social and environmental impacts.

5.2 Recommendation

The following are the major recommendations:

1. National environmental policies, particularly library-based ones, need stronger updating with active community engagement to turn rules into action and reinforce shared responsibility for protecting ecosystems.

2. Manufactured sand and gravel production is a largely untapped potential in Tigray and Ethiopia. The government should ensure that crusher operators follow green consumerism principles, including the polluter-pays principle, to support sustainable development. This can be achieved through actionable policies that enable operators to adopt energy-efficient technologies, recycle by-products, manage air pollution, ensure responsible sourcing and site rehabilitation, maintain transparency, and engage with local communities.
3. Regulatory authorities should enforce that crusher operators implement rainwater harvesting during the rainy season to secure water for dust control, reducing reliance on surface and ground water while promoting sustainable and environmentally friendly operations.
4. Regulatory authorities should provide the sites for crushers based on the local environment's carrying capacity, ensuring extraction stays within the resources and ecosystem limits to prevent socio-environmental impacts while supporting sustainable operations.
5. Regulatory authorities should invest in awareness, encouraging future research on why environmental policy in Ethiopia has weak in implementation, and capacity-building for crusher operators, communities, and other stakeholders to promote sustainable practices, ensure regulatory compliance, and protect the ecosystem long-term.

References

Ababa, A. (2025). Environmental and Social Impact Assessment.

Abate, Z. (2016). Impacts of Stone Quarrying on Environment and Livelihood of Local Community in Addis Ababa Peri-Urban Areas. *Unpublished MA Project, Addis Ababa University*.

Abbas, Z., & Jaber, H. S. (2020). Accuracy assessment of supervised classification methods for the extraction of land use maps using remote sensing and GIS techniques. IOP Conference Series: Materials Science and Engineering,

Abdulazeez, A. (2023). Dynamics and Impacts of Sand Mining in the Watari River Basin in Kano State, Nigeria. A Ph. D Geography Thesis. Department of Geography, Faculty of Earth and Environmental Sciences, Federal University Dutsin-Ma (FUDMA), Katsina State. In: iii.

Abera, W., Tamene, L., Tibebe, D., Adimassu, Z., Kassa, H., Hailu, H., Mekonnen, K., Desta, G., Sommer, R., & Verchot, L. (2020). Characterizing and evaluating the impacts of national land restoration initiatives on ecosystem services in Ethiopia. *Land Degradation & Development*, *31*(1), 37-52.

Achalu, B., Pavanasam, N., Bekele, N., & Mariappan, J. (2023). Impact of gravel mining on agricultural soils at Gorfo Mountain, West Shewa Zone, Ethiopia. *Arabian Journal of Geosciences*, *16*(5), 312.

Adanu, S. K., Boakye, M. K., Gbedemah, S. F., & Nyatuame, M. (2025). Perceptions of environmental and health effects of quarry activities at Klefe in the Ho municipality of the Volta region. *GeoHealth*, *9*(3), e2024GH001168.

Ahadzi, D. F., Afitiri, A. R., Ekumah, B., Kanatey, V., & Afedzi, A. (2020). Self-reported disease symptoms of stone quarry workers exposed to silica dust in Ghana. *Health science reports*, *3*(4), e189.

Akanwa, A. O., Hemmler, K. S., Park, E., Rangel-Buitrago, N. G., Nguyen, B. Q., Mei, Z., & Lamb, V. (2025). Toward a sustainable future of sand. *One Earth*, *8*(2).

Amour, R. R., & Haji, H. A. (2024). Geospatial Assessment of Impacts of Sand Mining Activities in Zanzibar. *Journal of ICT Systems*, *2*(1), 59-71.

Andualem, Z., Alemu, A. T., Geddif, A., Kassie, G. G., Mitiku, K. W., Belay, M. A., Simegn, M. B., Chanie, S. D., Tilahun, W. M., & Menber, Y. (2025). Impacts of climate change on chronic respiratory health in Ethiopia: a systematic review and meta-analysis. *Frontiers in Climate*, *7*, 1555383.

Aschale, M. A. (2025). Silica Sand Production Potential, Quality, and Market Analysis Case Study in the Kella Locality, South Sodo District, Ethiopia. *Quality and Market Analysis Case Study in the Kella Locality, South Sodo District, Ethiopia*.

Asgedom, A. A. (2023). Dust exposure and respiratory health among selected factories in Ethiopia: existing evidence, current gaps, and future directions. *Journal of Respiration*, *3*(2), 49-59.

Ashuro, Z., Hareru, H. E., Soboksa, N. E., Abaya, S. W., & Zele, Y. T. (2023). Occupational exposure to dust and respiratory symptoms among Ethiopian factory workers: A systematic review and meta-analysis. *Plos one*, *18*(7), e0284551.

Assefa, G., & Gebregziabher, A. (2020). Environmental impact and sustainability of aggregate production in Ethiopia. *Sandy Materials in Civil Engineering-Usage and Management*, 1-9.

ASTM, C. (2003). Standard specification for concrete aggregates. *Philadelphia, PA: American Society for Testing and Materials*.

Authority, E. P., & ABABA, A. (1997). Environmental policy. *Addis Ababa*.

Ayuk, E., Pedro, A., Ekins, P., Gatune, J., Milligan, B., Oberle, B., Christmann, P., Ali, S., Kumar, S. V., & Bringezu, S. (2020). *Mineral Resource Governance in the 21st Century: Gearing*

extractive industries towards sustainable development. International Resource Panel, United Nations Envio, Nairobi, Kenya.
Backman, J., & Minav, T. (2025). Improvement of Mobile Crusher Energy Efficiency Through Hybridization. Advancements in Fluid Power Technology: Sustainability, Electrification, and Digitalization: Proceedings of the Global Fluid Power Society PhD Symposium 2024,
Baffoe, G., Zhou, X., Moinuddin, M., Somanje, A. N., Kuriyama, A., Mohan, G., Saito, O., & Takeuchi, K. (2021). Urban–rural linkages: Effective solutions for achieving sustainable development in Ghana from an SDG interlinkage perspective. *Sustainability science*, *16*(4), 1341-1362.
Balcha, D., & Oyda, S. (2021). Assessing the impact of stone quarrying on the landscape, crop, and grazing land degradation in Loma Bosa district, Dawuro zone, southern Ethiopia. *International Journal of Scientific Research in Civil Engineering (IJSRCE)*, *5*(2), 79-91.
Bareke, T., & Addi, A. (2020). Bee flora diversity in different vegetation communities of Gesha-Sayilem forest in Kaffa Zone, south-western Ethiopia. *Plants and Environment*, *2*(4), 138-148.
Bareke, T., Alemu, T., Addi, A., Yimer, O., & Mengesha, D. (2025). Effects of honeybee pollination and other insect pollinators on increasing the seed yield and germination capacity of carrot (Daucus Carota L.) in the central highlands of Ethiopia. *BMC Plant Biology*, *25*(1), 1051.
Beiser, V. (2019). Why the world is running out of sand. *Bbc Future*, *18*(8).
Belay, T., Melese, T., & Terefe, B. (2025). Spatio-temporal dynamics of vegetation cover and land surface temperature in the North Gojjam sub-basin, Ethiopia. *Discover Applied Sciences*, *7*(12), 1408.
Bendixen, M., Iversen, L. L., Best, J., Franks, D. M., Hackney, C. R., Latrubesse, E. M., & Tusting, L. S. (2021). Sand, gravel, and UN Sustainable Development Goals: Conflicts, synergies, and pathways forward. *One Earth*, *4*(8), 1095-1111.
Bendixen, M., Noorbhai, N., Zhou, J., Iversen, L. L., & Huang, K. (2023). Drivers and effects of construction-sand mining in Sub-Saharan Africa. *The Extractive Industries and Society*, *16*, 101364.
Bikeko, S. S., & E V. (2024). Land use land cover change as a causal factor for climate variability and trends in the Bilate Watershed, Ethiopia. *Environmental Monitoring and Assessment*, *196*(12), 1250.
Chavez Jr, P. S. (1988). An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data. *Remote sensing of environment*, *24*(3), 459-479.
Chuvieco, E. (2020). *Fundamentals of satellite remote sensing: An environmental approach*. CRC Press.
Climatiq. (2017). *Ethiopia: Electricity supplied from grid – Emission Factor (0.0164 kgCO_2e/kWh)* https://www.climatiq.io/data/emission-factor/53303f04-3356-4436-a506-1fbcdc686363
Congalton, R., & Rekas, A. (1985). COMPAR- A computerized technique for the in-depth comparison of remotely sensed data. ASP, Annual Meeting, 51 st, Washington, DC,
Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote sensing of environment*, *37*(1), 35-46.
Congalton, R. G., & Mead, R. A. (1983). A quantitative method to test for consistency and correctness in photointerpretation. *Photogrammetric engineering and remote sensing*, *49*(1), 69-74.
Dentoni, V., Grosso, B., Massacci, G., & Soddu, G. (2020). Visual impact evaluation of mines and quarries: the updated Lvi method. *Environmental Earth Sciences*, *79*(5), 100.

Desa, U. (2019). World population prospects 2019: Highlights. *New York (US): United Nations Department for Economic and Social Affairs*, *11*(1), 125.

Dinh, C. (2020). Asia's Hunger for Sand is Harmful to Farming and the Environment. *The Economist*, *16*.

EEPA. (2025). *Environmental and Social Impact Assessment (ESIA) Guidelines for Mining Projects in Ethiopia*. https://www.epa.gov.et/images/licencing/Mining%20ESIA%20Guideline.pdf?utm_source=chatgpt.com

Eggen, M., Ozdogan, M., Zaitchik, B. F., & Simane, B. (2016). Land cover classification in complex and fragmented agricultural landscapes of the Ethiopian highlands. *Remote Sensing*, *8*(12), 1020.

Eggleston, H., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). 2006 IPCC guidelines for national greenhouse gas inventories.

Elnourani, M., Elhag, H. S. H., Alasad, W. I., & Bashier, M. N. (2024). Khartoum War's echoes in oil and energy sectors: Economic and environmental implications for Sudan and South Sudan. *Heliyon*, *10*(15).

EN 15804, U. (2012). Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products. In: European committee for standardization Brussels.

Endalew, A., Tasew, E., & Tolahun, S. (2019). Environment and social impacts of stone quarrying: South western Ethiopia, in case of Bahir Dar Zuria Wereda Zenzelma Kebele. *International Journal of Research in Environmental Science*, *5*(2), 29-38.

EPA. (2021). *What are heat islands?* https://www.epa.gov/heatislands/what-are-heat-islands

FAO. (2019). *International slope-range classification practices for land evaluation and capability assessment: Slope range classification standards*. https://www.gov.wales/sites/default/files/publications/2021-04/agricultural-land-classification-technical-review-part-1.pdf?utm_source=chatgpt.com

Farnham, A., Cossa, H., Dietler, D., Engebretsen, R., Leuenberger, A., Lyatuu, I., Nimako, B., Zabre, H. R., Brugger, F., & Winkler, M. S. (2020). Investigating health impacts of natural resource extraction projects in Burkina Faso, Ghana, Mozambique, and Tanzania: protocol for a mixed methods study. *JMIR research protocols*, *9*(4), e17138.

FEPA. (2022). *Report on Assessment of Greenhouse Gas (GHG) Mitigation Policy for Waste Management, Light Transit and Biofuel* https://www.epa.gov.et/images/PDF/Climatechange/GHG%20mitigation%20policy%20assessment%20EPA.pdf?utm_source=chatgpt.com

Foody, G. M. (2002). Status of land cover classification accuracy assessment. *Remote sensing of environment*, *80*(1), 185-201.

Forster, T., Egal, F., Romero Mera, C., & Escudero, A. G. (2021). Urban–Rural Linkages and Ecosystem Restoration. *UNCCD Global Land Outlook Working Paper. Bonn. Electronic file available at: https://www. unccd. int/sites/default/files/2022-03/UNCCD% 20GLO% 20WP% 20urban-rural% 20linkages. pdf Accessed*, *22*, 2023.

Gallagher, L., & Peduzzi, P. (2019). *Sand and sustainability: Finding new solutions for environmental governance of global sand resources*.

Gashaw, A., & Aklilu, G. (2020). Environmental impact and sustainability of aggregate production in Ethiopia. *Sandy Materials in Civil Engineering (Eds. Nemati, S. and Tahmoorian, F.)*.

Gebru, A. B., Gebreyohannes, T., & Kahsay, G. H. (2025). Modelling climate change and aridity for climate impact studies in semi-arid regions: The case of Giba basin, northern Ethiopia. *Heliyon*, *11*(1).

Gebru, E., Berhanu, A., Hayal, L., Solomon, A., & Tsehaye, A. (2016). Honey bee flora diversity and their impact on honey production in the Tigray region of Ethiopia. *Livestock Research for Rural Development*, *28*(7), 1-20.

Gemeda, F., Guta, D., Wakjira, F., & Gebresenbet, G. (2023). Land acquisition, compensation, and expropriation practices in the Sabata Town, Ethiopia. *Eur. J. Sustain. Dev. Res*, *7*(2), em0212.

Getachew, N., & Meten, M. (2021). Weights of evidence modeling for landslide susceptibility mapping of Kabi-Gebro locality, Gundomeskel area, Central Ethiopia. *Geoenvironmental Disasters*, *8*(1), 6.

Gitima, G., Tadesse, T., Berhanu, Y., Kassie, M., Jakubus, M., & Teshome, M. (2025). Impacts of land use and land cover changes on carbon stocks (1992–2052) Using geospatial technologies in Gena district, Southwest Ethiopia. *Scientific Reports*, *15*(1), 1-17.

Global-T. (2025). *Supply of Base Course (Crushed aggregate), Ethiopian Railways Corporation, Ethiopia has released a tender for Supply of Base Course (Crushed aggregate) in Metals and non-metals.* https://www.globaltenders.com/tender-detail/supply-of-base-course-crushed-aggregate-108924345?utm_source=chatgpt.com

Gondo, T., Amponsah-Dacosta, F., & Mathada, H. (2019). Regulatory and policy implications of sand mining along the shallow waters of Njelele River in South Africa. *Jàmbá: Journal of Disaster Risk Studies*, *11*(3), 1-12.

Gudissa, L., Raghuvanshi, T. K., Meten, M., & Chemeda, Y. C. (2021). TES analysis for crushed stone aggregate quarry site selection: the case of limestone terrain around Harer-Dire Dawa towns, Eastern Ethiopia. *Arabian Journal of Geosciences*, *14*(4), 315.

Ha, T. V., Tuohy, M., Irwin, M., & Tuan, P. V. (2020). Monitoring and mapping rural urbanization and land use changes using Landsat data in the northeast subtropical region of Vietnam. *The Egyptian Journal of Remote Sensing and Space Science*, *23*(1), 11-19.

Habtie, T. T., Teferi, E., & Guta, F. (2024). Multi-level determinants of land use land cover change in Tigray, Ethiopia: A mixed-effects approach using socioeconomic panel and satellite data. *Plos one*, *19*(6), e0304896.

Hackney, C., Vasilopoulos, G., Heng, S., Darbari, V., Walker, S., & Parsons, D. (2021). Sand mining far outpaces natural supply in a large alluvial river. *Earth Surface Dynamics Discussions*, *2021*, 1-20.

Hailu, T. G., Atsbeha, A. T., Wakjira, K., & Gray, A. (2024). High rates of honey bee colony losses and regional variability in Ethiopia based on the standardised COLOSS 2023 survey. *Insects*, *15*(6), 376.

Han, Y., Xu, W., Liu, J., Zhang, X., Wang, K., Wang, D., & Mei, Z. (2023). Ecological impacts of unsustainable sand mining: urgent lessons learned from a critically endangered freshwater cetacean. *Proceedings of the Royal Society B*, *290*(1990), 20221786.

Hemmler, K. S., Asare, K. Y., Tenkorang, E. Y., & Buerkert, A. (2024). Sand mining deteriorates soil fertility and farming livelihoods around Accra, Ghana. *Scientific Reports*, *14*(1), 17063.

Hougaard, I.-M., & Vélez-Torres, I. (2020). Shifting sands: Legal dispossession of small-scale miners in an extractivist era. *Geoforum*, *115*, 81-89.

Hudson, W. D. (1987). Correct formulation of the kappa coefficient of agreement. *Photogrammetric engineering and remote sensing*, *53*(4), 421-422.

Islam, S., Biswas, P. K., Saha, S., Sayem, A., & Khan, M. M. A. (2023). Occupational injuries and risk assessment among stone crushing industry workers: a cross-sectional study. *International archives of occupational and environmental health*, *96*(6), 903-917.
Jensen, J. R. (1996). Introductory digital image processing: a remote sensing perspective.
Kafu-Quvane, B., & Mlaba, S. (2024). Assessing the impact of quarrying as an environmental ethic crisis: A case study of limestone mining in a rural community. *International Journal of Environmental Research and Public Health*, *21*(4), 458.
Kamble, A., Patil, S., & Kanase, A. (2019). Comparative study on the strength and economy of conventional and high-performance concrete using crushed sand and river sand. *Int J Adv Res, Ideas Innov Technol*, *5*, 126-132.
Kassa, H., Birhane, E., Bekele, M., Lemenih, M., Tadesse, W., Cronkleton, P., Putzel, L., & Baral, H. (2017). Shared strengths and limitations of participatory forest management and area exclosure: two major state-led landscape rehabilitation mechanisms in Ethiopia. *International Forestry Review*, *19*(4), 51-61.
Kirkendall, N. J., & White, J. (2018). *Improving health research on small populations: proceedings of a workshop*. National Academies Press.
Kitole, F. A., Kalumanga, V. E., Hyera, D. W., & Evason, E. M. (2025). Risks, challenges and socioeconomic impacts of quarrying on rural livelihoods in Tanzania. *Cogent Social Sciences*, *11*(1), 2489040.
Kresojević, M., Ristić Vakanjac, V., Trifković, D., Nikolić, J., Vakanjac, B., Polomčić, D., & Bajić, D. (2023). The effect of gravel and sand mining on groundwater and surface water regimes—a case study of the Velika Morava river, Serbia. *Water*, *15*(14), 2654.
Langer, W. (2016). Sustainability of aggregates in construction. In *Sustainability of construction materials* (pp. 181-207). Elsevier.
Lasisi, M., Popoola, A., Adediji, A., Adedeji, O., & Babalola, K. (2017). City expansion and agricultural land loss within the peri-urban area of Osun State, Nigeria. *Ghana Journal of Geography*, *9*(3), 132–163-132–163.
LCP. (2023). *Electricity Generation Mix in Ethiopia* https://lowcarbonpower.org/region/Ethiopia
Leake, B., Emiru, B., & Amanuel, Z. (2020). Effects of stone mining on woody plant species diversity and selected soil properties in northern Ethiopia. Environ Syst Res 9 (12). In.
Lee, C., Asbjörnsson, G., Hulthén, E., & Evertsson, M. (2024). The environmental impact of extraction: A holistic review of the quarry lifecycle. *Cleaner Environmental Systems*, *13*, 100201.
Leow, J. (2020). "This land was the sea": The Intimacies and Ruins of Transnational Sand in Singapore. *Verge: Studies in Global Asias*, *6*(2), 167-189.
Lillesand, T., Kiefer, R. W., & Chipman, J. (2015). *Remote sensing and image interpretation*. John Wiley & Sons.
Liu, J. G., & Mason, P. J. (2016). *Image processing and GIS for remote sensing: techniques and applications*. John Wiley & Sons.
Maini, R., & Aggarwal, H. (2010). A comprehensive review of image enhancement techniques. *arXiv preprint arXiv:1003.4053*.
Mamaru, D. (2020). Suitability of crushed manufactured sand for the replacement of natural river sand to produce C-25 concrete. *J. Civ. Environ. Eng*, *10*(7).
Mamo, S. A., Kapito, M., & Suykens, B. (2024). River sand commodity chains in Ethiopia: governance, stakeholders, and socio-ecological implications.
Manger, G. E. (1963). *Porosity and bulk density of sedimentary rocks*.

Mariye, M., Jianhua, L., Maryo, M., Tsegaye, G., & Aletaye, E. (2024). Remote sensing and GIS-based study of land use/cover dynamics, driving factors, and implications in southern Ethiopia, with special reference to the Legabora watershed. *Heliyon*, *10*(1).
Mathewos, M., & Amare, B. (2022). Impact of aggregate washing and blending on concrete compressive. *Ethiopian Journal of Engineering and Technology*, *2*(1), 43-53.
Meaux, L., Cox, J., Edens, J. F., DeMatteo, D., Martinez, A., & Bownes, E. (2022). The Personality Assessment Inventory in US case law: A survey and examination of relevance to legal proceedings. *Journal of Personality Assessment*, *104*(2), 179-191.
Mekonnen, Z., Berie, H. T., Woldeamanuel, T., Asfaw, Z., & Kassa, H. (2018). Land use and land cover changes and the link to land degradation in Arsi Negele district, Central Rift Valley, Ethiopia. *Remote Sensing Applications: Society and Environment*, *12*, 1-9.
Micijevic, E., Haque, M. O., & Barsi, J. (2021). Radiometric performance of Landsat 8 Collection 2 products. Earth Observing Systems XXVI,
Misrak, Y., Genet, Y., & Muluye, K. (2023). The Demands and Contests of Constitutional Amendment in Ethiopia: Analysis on the 1995 Federal Democratic Republic of Ethiopia (FDRE) Constitution. *Insight on Africa*, *15*(1), 88-107.
Mitike, G., Motbainor, A., Kumie, A., Samet, J., & Wipfli, H. (2016). Review of policy, regulatory, and organizational frameworks of environment and health in Ethiopia. *Ethiopian Journal of Health Development*, *30*(1), 42-49.
Mundra, S., Sindhi, P., Chandwani, V., Nagar, R., & Agrawal, V. (2016). Crushed rock sand–An economical and ecological alternative to natural sand to optimize concrete mix. *Perspectives in Science*, *8*, 345-347.
Muriki, J. G., Wambugu, S., & Obando, J. (2024). Environmental impacts of quarry stone mining in igembe south sub county, Meru County. *International Journal of Arts, Humanities and Social Sciences Studies*, *9*(4), 14.
MWE. (2018). *National Guidelines for Small-Scale Irrigation Development in Ethiopia*. Addis Ababa, Ethiopia: Ministry of Water and Energy (MWE)Retrieved from https://imiset.gov.et/media/SSIGL-24__Technical_Specifications_Ver-6.pdf?utm_source=chatgpt.com

Negarit, G. (2002). Environmental Pollution Control Proclamation. *The House of Peoples' Representatives—Ethiopia*.
Nelson, K. S., Nguyen, T. D., Francois, J. R., & Ojha, S. (2023). Rural sustainability methods, drivers, and outcomes: A systematic review. *Sustainable Development*, *31*(3), 1226-1249.
Nemati, S., & Tahmoorian, F. (2020). *Sandy Materials in Civil Engineering: Usage and Management*. BoD–Books on Demand.
Nguyen, D.-T., Nguyen, D.-L., & Lam, M. N.-T. (2022). An experimental investigation on the utilization of crushed sand in improving workability and mechanical resistance of concrete. *Construction and Building Materials*, *326*, 126766.
Nursamsi, I., Phinn, S. R., Levin, N., Luskin, M. S., & Sonter, L. J. (2024). Remote sensing of artisanal and small-scale mining: A review of scalable mapping approaches. *Science of the total environment*, *951*, 175761. https://www.sciencedirect.com/science/article/pii/S0048969724059175?via%3Dihub
Oates, J. A. (2008). *Lime and limestone: chemistry and technology, production and uses*. John Wiley & Sons.
OECD. (2021). *OECD Regional Development Studies Applying the Degree of Urbanisation A Methodological Manual to Define Cities, Towns and Rural Areas for International*

Comparisons: A Methodological Manual to Define Cities, Towns and Rural Areas for International Comparisons. OECD Publishing.
Pal, S., & Mandal, I. (2021). Impacts of stone mining and crushing on environmental health in the Dwarka river basin. *Geocarto International*, *36*(4), 392-420.
Peppas, A., Kottaridis, S., & Politi, C. (2024). Environmental assessment of alternative fuels utilisation in heavy transport operations for extractive industries. *Next Energy*, *5*, 100173.
Poonia, K., Kansara, P., & Choudhary, P. (2024). Environmental impacts of sand mining: A comprehensive review. *International Advanced Research Journal in Science, Engineering and Technology*, *11*(3).
Rafi, M. M., & Aziz, T. (2022). Experimental testing of fly ash-containing recycled aggregate concrete exposed to high temperatures. *Sustainable and Resilient Infrastructure*, *7*(1), 1-16.
Redi, T. (2024). A Critical Reflection on Air Quality Monitoring in Ethiopia: Challenges, Progress, and the Way Forward. *Clean Air Journal*, *34*(2), 1-2.
Rehman, G., Hamayun, M., Rahman, A., Haseeb, M., Umar, M., Ali, S., Shams, W., & Pervaiz, R. (2021). Impacts of mining on the local fauna of wildlife in District Mardan & District Mohmand, Khyber Pakhtunkhwa, Pakistan. *Brazilian Journal of Biology*, *84*, e251733.
Ren, Z., Jiang, M., Chen, D., Yu, Y., Li, F., Xu, M., Bringezu, S., & Zhu, B. (2022). Stocks and flows of sand, gravel, and crushed stone in China (1978–2018): Evidence of the peaking and structural transformation of supply and demand. *Resources, Conservation and Recycling*, *180*, 106173.
Ricigliano, V. A., Fine, J. D., & Nicklisch, S. C. (2025). Harnessing biotechnology for bee pollinator health. *Trends in Biotechnology*.
Rwanga, S. S., & Ndambuki, J. M. (2017). Accuracy assessment of land use/land cover classification using remote sensing and GIS. *International Journal of Geosciences*, *8*(04), 611.
Sairanen, M., & Rinne, M. (2019). Dust emission from crushing of hard rock aggregates. *Atmospheric Pollution Research*, *10*(2), 656-664.
Saleem, H. A., & Ayalew, A. T. (2025). Enhancing environmental sustainability and operational efficiency in a case study of a limestone quarry in an arid climate. *Scientific Reports*, *15*(1), 18884.
Seblework, D. (2006). Occupational safety and health profile for Ethiopia. *Ministry of Labour and Social Affairs*.
Shewatatek, D., Tenaw, B., Yemiru, A., Belete, G., Tadesse, T., & Tolla, T. (2022). Characteristics of sand at major quarrying areas around Addis Ababa. *Advances in Civil Engineering*, *2022*(1), 3198879.
Simarjeet, K. (2017). Sample size determination (for descriptive studies). *Int. J. Curr. Res*, *9*, 48365-48367.
Sime, G., & Aune, J. B. (2019). Rural livelihood vulnerabilities, coping strategies and outcomes: a case study in the central rift valley of Ethiopia. *African Journal of Food, Agriculture, Nutrition and Development*, *19*(3), 14602-14621.
Singh, S., Singh, S. K., Kumar, R., Shrama, A., & Kanga, S. (2022). Finding an alternative to river sand in building construction.
Smits, P., Dellepiane, S., & Schowengerdt, R. (1999). Quality assessment of image classification algorithms for land-cover mapping: a review and a proposal for a cost-based approach. *International journal of remote sensing*, *20*(8), 1461-1486.
Srivastava, P. K., Han, D., Rico-Ramirez, M. A., Bray, M., & Islam, T. (2012). Selection of classification techniques for land use/land cover change investigation. *Advances in Space Research*, *50*(9), 1250-1265.

Standard, I. (2016). Coarse and fine aggregate for concrete–Specification. *Bureau of Indian Standards, New Delhi*.

Steen, W. (1936). *The Ethiopian Constitution*. Рипол Классик.

Story, M., & Congalton, R. G. (1986). Accuracy assessment: a user's perspective. *Photogrammetric engineering and remote sensing*, *52*(3), 397-399.

Sultan, M. A., Ahmad, I., Arif, M., Sadaf, S., Kamran, M., Abbas, T., Shaffique, S., & Gatasheh, M. K. (2025). Anthropogenic dust pollution influences leaf and root morpho-anatomical traits by altering the metabolism and biochemical properties of indigenous vegetation. *Environmental Geochemistry and Health*, *47*(8), 314.

Sun, Z., Ma, R., & Wang, Y. (2009). Using Landsat data to determine land use changes in the Datong basin, China. *Environmental geology*, *57*, 1825-1837.

Susca, T., Gaffin, S. R., & Dell'Osso, G. (2011). Positive effects of vegetation: Urban heat island and green roofs. *Environmental pollution*, *159*(8-9), 2119-2126.

Sutton, P. C., Anderson, S. J., Costanza, R., & Kubiszewski, I. (2016). The ecological economics of land degradation: Impacts on ecosystem service values. *Ecological Economics*, *129*, 182-192.

Sverdrup, H. U., Koca, D., & Schlyter, P. (2017). A simple system dynamics model for the global production rate of sand, gravel, crushed rock, and stone, market prices, and long-term supply is embedded into the WORLD6 model. *BioPhysical Economics and Resource Quality*, *2*(2), 8.

Swift, A., Smoorenburg, E., Newman, A., & Bogin Jr, G. E. (2023). The impact of environmental conditions on the heat and emissions produced by large diesel engines in underground mines. *Journal of Cleaner Production*, *429*, 139277.

Tacoli, C. (2003). The links between urban and rural development. In (Vol. 15, pp. 3-12): Sage Publications, Sage CA: Thousand Oaks, CA.

Tan, L. M., Arbabi, H., Densley Tingley, D., Brockway, P. E., & Mayfield, M. (2021). Mapping resource effectiveness across urban systems. *npj Urban Sustainability*, *1*(1), 20.

Tan, Y., Ma, C., Zhao, B., Xiong, W., Chen, X., & Yu, J. (2023). Study and microanalysis on the effect of the addition of polypropylene fibres on the bending strength and carbonization resistance of manufactured sand concrete. *Polymers*, *15*(9), 2139.

Tang, Y., Xiao, J., Liu, Q., Xia, B., Singh, A., Lv, Z., & Song, W. (2022). Natural gravel-recycled aggregate concrete applied in rural highway pavement: Material properties and life cycle assessment. *Journal of Cleaner Production*, *334*, 130219.

Teferi, E., Kassawmar, T., Bewket, W., Zeleke, G., Ayele, G. T., O'Donnell, G., & Walsh, C. (2025). Rainfed agriculture in Ethiopia: a systematic review of green water management pathways to improve water and food security. *Frontiers in Agronomy*, *7*, 1418024.

Tegegne, A. G. (2022). Ethiopian Environmental Impact Assessment Proclamation NO. 299/2002Vis a Vis Other Sectoral Laws. *International and Public Affairs*, *6*(2), 29-37.

Teku, D. (2025). Geo-environmental and socio-economic impacts of artisanal and small-scale mining in Ethiopia: challenges, opportunities, and sustainable solutions. *Frontiers in Environmental Science*, *13*, 1505202.

Tesfaye, B., Lengoiboni, M., Zevenbergen, J., & Simane, B. (2021). Mapping land use land cover changes and their determinants in the context of a massive free labour mobilisation campaign: Evidence from South Wollo, Ethiopia. *Remote sensing*, *13*(24), 5078.

Thapa, K., Sukhwani, V., Deshkar, S., Shaw, R., & Mitra, B. K. (2020). Strengthening urban-rural resource flow through the regional circular and ecological sphere (R-CES) approach in Nagpur, India. *Sustainability*, *12*(20), 8663.

TheGlobalEconomy.com. (2024). *Female Labor Force Participation – Ethiopia*. TheGlobalEconomy.com. https://www.theglobaleconomy.com/Ethiopia/Female_labor_force_participation/
Torres, A., Brandt, J., Lear, K., & Liu, J. (2017). A looming tragedy of the sand commons. *Science*, *357*(6355), 970-971.
Torres, A., Simoni, M. U., Keiding, J. K., Müller, D. B., zu Ermgassen, S. O., Liu, J., Jaeger, J. A., Winter, M., & Lambin, E. F. (2021). Sustainability of the global sand system in the Anthropocene. *One Earth*, *4*(5), 639-650.
U.S.EPA. (2023). *AP-42: Compilation of Air Pollutant Emission Factors, Chapter 11.19.2—Crushed Stone Processing and Pulverized Mineral Processing*. U.S of America: U.S. Environmental Protection Agency (if your style asks for a publisher distinct from the author, here it is the same). Retrieved from https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors
Üçtuğ, F. G., Ediger, V. Ş., Küçüker, M. A., Berk, İ., İnan, A., & Moghadasi Fereidani, B. (2025). Cradle-to-gate life cycle assessment of heavy machinery manufacturing: a case study in Türkiye. *The International Journal of Life Cycle Assessment*, *30*(5), 939-955.
Upadhyaya, M. K. (2021). Effect of Occupational Silica Exposure on Stone Crusher Workers.
USEPA. (2020). *Update of emission factors of greenhouse gases and criteria air pollutants, and generation efficiencies of the US electricity generation sector*.
Vasilyeva, N., Golyshevskaia, U., & Sniatkova, A. (2023). Modeling and improving the efficiency of crushing equipment. *Symmetry*, *15*(7), 1343.
Vélez-Torres, I., Lugo-Vivas, D. A., & Swistun, D. A. (2024). Toxic dispossession and environmental violence in Latin America. *Journal of Political Ecology*, *31*, 6091.
Vermote, E., Justice, C., Claverie, M., & Franch, B. (2016). Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product. *Remote sensing of environment*, *185*, 46-56.
Vestal, T. M. (1996). An analysis of the new constitution of Ethiopia and the process of its adoption. *Northeast African Studies*, *3*(2), 21-38.
Vural, N., Yılmaz, M., Onat, B., & Tuğrul, A. (2025). Life cycle assessment of sandstone aggregate quarry activities—a case study in Istanbul, Türkiye. *The International Journal of Life Cycle Assessment*, *30*(5), 862-879.
WOLF, M.-A., CHOMKHAMSRI, K., BRANDAO, M., PANT, R., ARDENTE, F., PENNINGTON, D., MANFREDI, S., DE, C. C., & GORALCZYK, M. (2010). International Reference Life Cycle Data System (ILCD) handbook: general guide for life cycle assessment-detailed guidance.
Wondimu, A. (2021). Environmental and Social Impacts of Stone Quarrying Activities in Addis Ababa: In the case of Bole Sub City. *Oshe Locality*.
Worku, H. (2017). Environmental and socioeconomic impacts of cobblestone quarries in Addis Ababa and implications for resource use efficiency, environmental quality, and sustainability of land after-use. *Environmental Quality Management*, *27*(2), 41-61.
Worku, Z., Bihonegn, A., Begna, D., Ababor, S., & Gebeyehu, A. (2022). The indirect threats of desert locust infestation on honeybees in Ethiopia. *Advances in Agriculture*, *2022*(1), 4269565.
Wulder, M. A., Loveland, T. R., Roy, D. P., Crawford, C. J., Masek, J. G., Woodcock, C. E., Allen, R. G., Anderson, M. C., Belward, A. S., & Cohen, W. B. (2019). Current status of Landsat program, science, and applications. *Remote sensing of environment*, *225*, 127-147.
Yamane, T. (1973). Statistics: An introductory analysis.

Yao, G., Chen, X., Li, J., & Zhang, L. (2022). Environmental performance and sustainability assessment of manufactured sand production for construction use. *Construction and Building Materials*, *331*, 127–145. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2022.127145

Yosef, T., & Shifera, N. (2023). Personal protective equipment utilization and associated factors among industry park construction workers in northwest Ethiopia. *Environmental health insights*, *17*, 11786302231185683.

Yusuf, Y. (2014). *Fine aggregate production and its environmental impact in some selected sites of the Rift Valley area in Ethiopia,* Addis Ababa University.

Zhao, P., Hu, H., & Yu, Z. (2025). Investigating the central place theory using trajectory big data. *Fundamental Research*, *5*(3), 1084-1096. https://www.sciencedirect.com/science/article/pii/S2667325823002431?via%3Dihub

Annex-1: Letter of consent & research questionnaires

Research Title: *Assessing urban-rural linkage in terms of local construction material use in Mekelle and surrounding areas: Tigray/Ethiopia*

Researcher: *Haftay Tsegay*

Dear Participants,

I am a graduate student at *EIT-M* conducting research for my master's degree. My study aims to *assess the impact of urban-rural linkage in terms of local construction material flow: "The case of Mekelle and the surrounding rural areas*." Participation involves *25-minute interviews and the sharing of relevant observations.* Your involvement is entirely voluntary. You may refuse to answer any question or withdraw at any time without penalty.

All information you provide will be kept strictly confidential and used only for academic purposes. Your name or identifying details will not appear in any report or publication.

Before we proceed to the next steps, please read the above information and voluntarily agree to take part in this research.

With regards

Part -1: *Profile* **of the household survey questionnaire**

1. Administrative Location: _____
2. Sex: _____
3. Age: _____
4. Level of education attained: _____
5. Family size _____

Part II: Open and closed-ended research questionnaires

Specific objective-1.1: Material flow (sand and gravel)

2.1.1.1 Water and energy (electricity and fuel) usage

6. How much diesel is used daily by each vehicle/machine type
7. Crushers_____loaders_____, dozers, _____ trucks_____ and water trucks_____
8. How much electricity is consumed per day to produce the total volume of
9. Gravel_____and sand_____
10. How much water is consumed daily? _____for what purpose used? _____
11. Have you considered the emissions' negative impact on the environment? A) Yes B) No
12. If the response is "Yes", how do you estimate the GHG emissions from energy use (fuel and electricity) consumption (site level)? _____
13. If the response is "Yes", how do you estimate the GHG emissions from energy use (fuel and electricity) consumption (site level)? _____

2.1.1.2 Material output and distribution

14. What are your daily working hours? _____monthly working days_____and yearly working days___
15. What is the estimated volume sand_____and Gravel_____crushed per day? _____How much of it was converted into usable output? _____sand_____Gravel
16. How do you calculate the total production volume per day/ monthly, /Yearly? _____
17. How is the useful product material distributed to Mekelle city only? _____

Specific objective-1.2: Environmental and Socio-economic Impacts

18. How does sand ang gravel production benefit rural and urban community: _____
19. What social problems or challenges have you observed due to sand and gravel production?

20. Describe the environmental impacts at both the rural and urban centers. _____
21. How do these environmental problems affect local communities and the ecosystem? _____
22. What are the major land use and land cover changes negatively impacted by the sand and gravel expansion from 2005 to 2025? _____
23. How much of the sand and gravel operation? _____
24. Are there conflicts between workers, investors, and local communities? A) Yes B) No
25. If the response is "Yes", please describe it. _____
26. How have the land use and land cover changes affected local socio-economic activities such as honey bee production, grazing land, crop production, etc.? _____

Specific objective: 1.3: Currently practiced mitigation measures to reduce environmental and social impacts and their effects

27. Were there agreed mitigation measures to be performed by the investors? A) Yes B) No C) I have no information, or it is not clear to me
28. If yes, please describe each agreed mitigation measure. _____
29. Currently, what types of these mitigation measures are being practiced to reduce environmental and social risks? _____
30. If no, or I have no information, or it is not clear to me, please describe the reasons. _____
31. What challenges have you observed in implementing these mitigation measures? _____
32. What type of support was provided by the woreda or regional authorities to implement mitigation measures? _____
33. Were the investors initially discussed with the local community? A) Yes B) No
34. If the Response is: No," with whom were they discussed, and what problems were raised at the community level?
35. Are there any capacity-building or awareness programs provided by the local authorities or investors to support compliance? A) Yes B) No

Section 1.4- Key informant Questionnaires

Farmers

36. How has leasing your land for sand and gravel production affected your livelihood and farming activities?

37. What compensation or support have you received from investors, and was it adequate?
38. What recommendations do you have to improve agreements between farmers and investors?

Experts (environmentalists/social/engineers/natural resources)

39. What are the main risks and challenges associated with sand and gravel production in these areas?
40. How effective are current mitigation measures in reducing environmental and social impacts?
41. How well are legal and regulatory requirements applied at the sites?
42. What policy or practices would you recommend to improve sustainable production and compliance?

Woreda and regional staff

43. What support does your office provide to monitor and manage sand and gravel production sites?
44. What challenges do you face in enforcing laws and supporting sand and gravel operations?
45. Have you embedded the local communities from the very beginning of the crusher's installation? For how many years have you agreed with the investors?
46. What types of mitigation measures were embedded in the agreement? Do you think the investors are implementing as per the agreed-upon points? Please describe this, including the reasons for not implementing as per the agreement.
47. What recommendations do you have to improve policy enforcement, legal compliance, and community engagement?

Annex II: Calculations

Annex II (a): Volume of material flow and GHG emission calculation

This section focused on calculating the total amount of useful and waste (non-usable) sand and gravel produced in the study areas. The calculation was carried out using data that were measured and collected directly from each production site. These data included the daily working hours, the average daily production, the number of working days per month and per year, and the months that were unsuitable for local construction material production due to seasonal or weather-related factors. Also, the efficiency of the crushers was considered to determine how effectively each crusher converted the total amount of raw material into usable sand and gravel.

Using these collected variables, the total annual production volume of sand and gravel was estimated. This total was then converted into various units of measurement, such as cubic meters and tons, to facilitate the calculation of other related parameters. The specific gravity of the sedimentary rocks and hard limestone used in the calculation process was also applied. These values were obtained from internationally recommended standards, but were selected to reflect the local geological conditions based on a thorough literature review and supporting evidence. The researcher divided the overall calculation process into six main steps to make it clearer and more understandable for readers.

Calculating /Estimating the annually produced volume of construction material flow

Given site-level collected data similarity on:

- Daily working hours = 8 hours
- Daily average production of sand through crushing sedimentary rock = 404 m^3/day, and gravel/aggregate = 384m^3/day
- Monthly working days are 22 days/month
- Non-working months per year = 2 months (July and August- rainy time)
- Yearly working days = 220 days/Year

Taking these data per study area, the total volume of sand and gravel produced per site level was estimated using the following equations (2-8) presented on page 22.

Step 1: First, calculate the daily production of sand and gravel at both study areas.

- Daily produced sand through crushing sedimentary rock = 404 m^3/day, and gravel/aggregate = 384m^3/day -site level measured values.

Step 2: Calculate monthly sand and gravel production using the equation

a) Monthly sand production:

$$\text{Monthly sand production} = \left[D_p x M_d = D_p x 22 \frac{\text{days}}{\text{month}}\right] \quad \ldots\ldots\ldots\ldots\ldots\text{eqn (3)}$$

From step-1, Daily production (Dp) = 404 m^3/day

$$\text{Monthly sand production} = 404 \frac{m^3}{\cancel{day}} x 22 \frac{\cancel{day}}{\text{month}}$$

$$\mathbf{Monthly\ sand\ production} = \mathbf{8,888} \frac{\mathbf{m^3}}{\mathbf{month}}$$

b) Monthly Gravel /aggregate production:

From step-1, Daily production (Dp) = 384 m^3/day

$$\text{Then, monthly gravel production} = 384 \frac{m^3}{\cancel{day}} x 22 \frac{\cancel{day}}{\text{month}}$$

$$\mathbf{Monthly\ gravel\ production} = \mathbf{8,448} \frac{\mathbf{m^3}}{\mathbf{month}} = \mathbf{384} \frac{\boldsymbol{m^3}}{\boldsymbol{day}}$$

Step 3: Calculate annual sand and gravel production (A_p) using equation (4)

$$[A_p] = \left[Y_d x M_p = 220 \frac{days}{year} x M_p\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eqn (4)}$$

i) Annual gravel production

From step 2, monthly gravel production ($Mp_{(gravel)}$) = $8{,}448 \frac{m^3}{month}$ = 384 m3/days

$$\text{Thus, Yearly gravel production } (Y_{d\,(gravel)} = 220 \frac{\text{day}}{\text{year}} x\ 8{,}448 \frac{m^3}{\text{month}}$$

$$= 220 \frac{\cancel{days}}{\text{year}} x\ 8{,}448 \frac{m^3}{22\ \cancel{days}} = \mathbf{84,480} \frac{\mathbf{m^3}}{\mathbf{year}}$$

ii) Annual sand production

From step 2, monthly sand production ($Mp_{(sand)}$) = $8{,}888 \frac{m^3}{month} = 404 \frac{m^3}{day}$

$$\text{Yearly gravel production } (Y_{d\,(gravel)} = 220 \frac{\text{day}}{\text{year}} x\ 8{,}888 \frac{m^3}{\text{month}}$$

$$= 220 \frac{\cancel{days}}{\text{year}} x\ 8{,}888 \frac{m^3}{22\ \cancel{days}} = \mathbf{88,880} \frac{\mathbf{m^3}}{\mathbf{year}}$$

iii) Calculate the average sand and gravel production in cubic meters per year

$$\text{Average (sand and gravel)production} = \frac{\text{Yearly gravel} + \text{Yealy sand}}{2}$$

$$= \frac{84{,}480+88{,}880}{2} \frac{m^3}{year} = \frac{173{,}360}{2} \frac{m^3}{year} = \mathbf{86,680} \frac{\boldsymbol{m^3}}{\boldsymbol{year}}$$

Step-4: Calculate useful sand and gravel production or output using equation (5)

$$[U_p] = [T_c x\ E] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eqn (5)}$$

a) Total useful sand per year

- Total calculated sand production per year (useful + byproduct) =$\mathbf{88,880} \frac{\mathbf{m^3}}{\mathbf{year}}$
- Conversion efficiency sand $\cong 75\%$ $= \frac{88{,}880 m3}{year} x\ 0.75 \cong \mathbf{66,660} \frac{\boldsymbol{m^3}}{\boldsymbol{year}}$

From this byproduct = $\frac{(88{,}880-66{,}660) m^3}{year} = \mathbf{22,220} \frac{\boldsymbol{m^3}}{\boldsymbol{year}}$

b) Total useful gravel per year

- Total calculated gravel production per year (useful + byproduct) =$\mathbf{84,480\frac{m^3}{year}}$
- Conversion efficiency sand ≅ 95% = $\frac{84{,}480\ m^3}{year} x\ 0.95 \cong \mathbf{80,256\frac{m^3}{year}}$

From this byproduct = $\frac{(84{,}480-80{,}256)m^3}{year} = \mathbf{4,224\frac{m^3}{year}}$

c) Total average useful and by-products of sand and gravel

i) Total average useful = $\frac{\text{Useful output (sand)+Useful output (gravel)m3}}{2}\frac{}{\text{year}}$

$$= \frac{\mathbf{66,660 + 80,256\frac{m^3}{year}}}{\mathbf{2}} = \frac{\mathbf{146,916}}{\mathbf{2}}\frac{\mathbf{m^3}}{\mathbf{year}} = \mathbf{73,458\frac{m^3}{year}}$$

ii) Total average byproduct= $\frac{\text{Not useful output (sand)+Not useful output (gravel)m3}}{2}\frac{}{\text{year}}$

$$= \frac{\mathbf{22,220 + 4,224\frac{m^3}{year}}}{\mathbf{2}} = \frac{\mathbf{26,444}}{\mathbf{2}}\frac{\mathbf{m^3}}{\mathbf{year}} = \mathbf{13,222\frac{m^3}{year}}$$

Step 5: Convert the total mass of sand and gravel produced (m^3/year into tons/year using equations 6 and 7

a) Use equation (6) for sand:

i) Total sand output (useful and not useful)

$[M_t] = \left[T_{Output\ (useful+not\ useful)}\ x1.6\frac{t}{m^3}\right]$..... eqn (6)

$$= 88{,}880\frac{\cancel{m^3}}{year}x1.6\frac{t}{\cancel{m^3}} = 142{,}208\frac{t}{year}$$

ii) Useful output = $66{,}660\frac{m^3}{year}x1.6\frac{t}{\cancel{m^3}} = 106{,}656\frac{t}{year}$

iii) Not useful output $= 142{,}208\frac{t}{year} - 106{,}656\frac{t}{year} \cong \mathbf{35,552\frac{t}{year}}$

b) Use equation (7) for gravel:

$$[M_t] = \left[T_{Output\ (useful+not\ useful)}\ x2.6\frac{t}{m^3}\right]\text{... eqn (7)}$$

1) Total sand output (useful and not useful) = $\mathbf{84,480\frac{m^3}{year}} \times 2.6\frac{t}{m^3} = 219{,}648\frac{t}{year}$

2) Useful output = $80,256\frac{\cancel{m3}}{year} \times 2.6\frac{t}{\cancel{m^3}} = 208{,}665.6\frac{t}{year}$

3) Not useful output $= 219{,}648\frac{t}{year} - 208{,}665.6\frac{t}{year} \cong \mathbf{10,982.4\frac{t}{year}}$

Sep 6: Total average sand and gravel produced t/year)- use equation (8)

$$[A_t] = \left[\frac{Total\ sand\ production + Total\ Gravel\ production}{2}\right]\text{..... eqn (8)}$$

i) Total (sand and gravel) in tons/year = $\frac{219{,}648\frac{t}{year}+142{,}208\frac{t}{year}}{2} = \mathbf{180,928\frac{t}{year}}$

ii) Useful output (sand and gravel) = $\frac{106{,}656\frac{t}{year}+208{,}666\frac{t}{year}}{2} = \mathbf{157,661\frac{t}{year}}$

iii) **Not useful** output **(sand +gravel) =** $\frac{35{,}552\frac{t}{year}+10{,}982\frac{t}{year}}{2} = \mathbf{23,267\frac{t}{year}}$

Annex-II(b): Calculation/Estimating GHG emissions from material flow

This section focuses on calculating greenhouse gas emissions from material flows, particularly those resulting from energy use, electricity, and diesel, during the manufacturing of sand and gravel. As shown in the table below, total diesel consumption was collected from each site based on the type and number of vehicles currently operating across the seven crushers. Electricity consumption for each study area was obtained from annual electricity bills. The overall analysis of these calculations is presented in the results and discussion part (Chapter four), where it is compared and contrasted with related findings from other parts of the country.

Site-level measured values: life cycle inventory -data (Annex V)

Input category	Flow description (on-site level)	Total annual energy consumption		Total on average
		Site messebo (Gravel)	Site Hareko (sand)	
Diesel fuel	Loaders, trucks, excavators, and crushers	132,456L/year	167,890 L/year	150,173 L/Year
Electricity	Crushers	605,000 kWh/year	134,450kWh/Year	369,725 kWh/Year
Net fresh water	Dust supervision (spraying, non-recycled)	29,141 m^3 /Year	41,051 m^3 /Year	21,596 m^3 /Year

Step-1: Calculate GHG emissions (CO_2e) from electric consumption using equation (9)

$$CO2_{electric} = [\text{Annual Electricity consumption kWh}]x[\text{Grid EF}]$$

Give from the table

- The total electric consumption measured from both study areas is 369,725 kWh/Year
- Based on the Ethiopian grid's Emission factor from the GHG protocol/climatic data (2017) is reported as 0.0164 kg CO2e/kWh

$$CO2_{electric} = \left[369{,}725\ \frac{\text{kWh}}{\text{Year}}\right] x \left[0.0164\ \frac{\text{kgCO2e}}{\text{kWh}}\right]$$

$$CO2_{electric} = \left[369{,}725\ \frac{\cancel{\text{kWh}}}{\text{Year}}\right] x \left[0.0164\ \frac{\text{kgCO2e}}{\cancel{\text{kWh}}}\right] = 6{,}063.49\ \frac{\text{kgCO2e}}{\text{Year}}$$

Step 2: Calculate GHG emissions (CO_2e) from electric consumption using equation (10)

$$CO2_{diesel} = [\text{Annual diesel consumption in litter }]x[\text{Emission factor for diesel}]$$

Given

- The average diesel consumption measured from both study areas is 1150,173 L/Year

- Based on the Ethiopian Environmental Protection Authority 2022 report, the emission factor for diesel consumption is approximately 2.65kg CO2e/L

$$\mathrm{CO2}_{\mathrm{diesel}} = \left[\frac{150{,}173\ L}{year}\right] \mathrm{x} \left[2.65\ \frac{\mathrm{kgCO2e}}{\mathrm{L}}\right] = \left[\frac{150{,}173\ \cancel{\mathrm{L}}}{\mathrm{Year}}\right] \mathrm{x} \left[2.65\ \frac{\mathrm{kgCO2e}}{\cancel{\mathrm{L}}}\right]$$

$$\mathbf{CO2_{diesel} = 397,958.45\ \frac{kgCO2e}{Year}}$$

Step 3: Calculate the total GHG emissions (CO_2e) from diesel and electric consumption using equation (12)

$$\mathrm{Total\ CO_2e} = \mathrm{CO2}_{\mathrm{electric}} + \mathrm{CO2}_{\mathrm{diesel}}$$

From the step 1 and step 2 calculation results

$$\mathrm{CO2}_{\mathrm{electric}} = 6{,}063.49\ \frac{\mathrm{kgCO2e}}{\mathrm{Year}} = 397{,}958.45\ \frac{\mathrm{kgCO2e}}{\mathrm{Year}}$$

$$\mathbf{Total\ CO_2e = 6,063.49\ \frac{kgCO2e}{Year} + 397,958.45\ \frac{kgCO2e}{Year} = 404,021.94\ \frac{kg\ CO2e}{Year}}$$

Step 4: Convert the total CO_2e using equation (11)

$$CO_2\mathrm{e\ per\ tone} = \frac{[\text{Annual diesel consumption(L)}]\mathrm{x}[\text{EF for diesel}]}{\text{Annual production (t)}} \ldots\ldots\ldots\ldots \text{ eqn (11)}$$

$$= \frac{\mathrm{Total\ CO^2e}}{\mathrm{Total\ Mass}}$$

$$= \frac{404{,}021.94\ \mathrm{kg}\ \frac{\mathrm{CO2e}}{\mathrm{Year}}}{\frac{180{,}928\ ton}{year}} = \frac{404{,}021.94\ \mathrm{kg}\ \frac{\mathrm{CO2e}}{\cancel{\mathrm{Year}}}}{\frac{180{,}928\ ton}{\cancel{year}}}$$

$$\mathbf{CO^2e\ to\ per\ ton = 2.23\ \frac{kgCO2e}{t}}$$

Annex II (c): Dust supervision efficiency calculation

This section also focuses on evaluating dust suppression efficiency by calculating both controlled and uncontrolled dust emissions in the seven local construction material production sites. Dust suppression primarily aims to reduce airborne particulate emissions from sand and gravel crushers, thereby improving air quality, protecting human health, ensuring regulatory compliance, enhancing operational safety, and fostering positive community relations. Accordingly, the efficiency of dust control through water spraying was determined using the following procedures and formulas.

Step 1: Calculate the uncontrolled emission using equation (13)

$$\mathbf{U_e = [EF]x[M_t]}$$

Given: Emission factor = 0.006lb/ton

: Total mass or volume of sand and gravel output = $\mathbf{180,928}$ ton/year

$$\mathbf{U_e} = \left[\frac{\mathbf{0.006lb}}{\mathbf{t}}\right]\mathbf{x}\left[\mathbf{180,928}\ \frac{ton}{year}\right] = \left[\frac{\mathbf{0.006lb}}{\mathbf{\cancel{ton}}}\right]\mathbf{x}\left[\mathbf{180,928}\ \frac{\cancel{ton}}{year}\right]$$

$$\mathbf{U_e = 1,085.57\frac{lb}{year} = 492.41\frac{kg}{year} = 0.492\frac{tonnes}{year}}$$

Step 2: The control efficiency of water spraying was determined by considering local operating conditions. A value of 70% was adopted, based on U.S. EPA guidelines for gravel and sand production crushers. This value is internationally recognized, particularly for operations without access to advanced monitoring equipment. Thus, $\mathbf{C_e}$ =70%

Step-3: Calculate Controlled emission using equation (14)

$$\mathbf{C_E = [Ue]x[1 - C_e]}$$

Given: Uncontrolled emission (U_e) = 1,085.57 lb/year (calculated result)

$$\mathbf{C_E} = \left[1{,}085.57\frac{\text{lb}}{\text{yeay}}\right]\mathbf{x[1 - 0.7]} = \left[1{,}085.57\frac{\text{lb}}{\text{yeay}}\right]\mathbf{x[0.3]}$$

$$\mathbf{C_E = 325.67\frac{lb}{yeay} = 147.7\frac{kg}{year} = 0.148\frac{tones}{year}, 1\ lb = 0.454kg}$$

Step-4: Calculate Absolute reduction ($\mathbf{A_r}$) (15)

$$\mathrm{A_r = U_e - C_E} = 1{,}085.6\frac{\text{lb}}{\text{year}} - 325.7\frac{\text{lb}}{\text{year}} = 759.3\frac{\text{lb}}{\text{year}}$$

$$= 344.7\frac{\text{kg}}{\text{year}} = \mathbf{0.345\frac{tonnes}{year}, removed\ per\ year\ by\ water\ spraying}$$

Step-5: Calculate/check the control efficiency equation (16)

$$\boldsymbol{C_e} = \left[\frac{\text{Absolute reduction}}{\text{Uncontrolled dust emission}}\right] = \left[\frac{759.3\frac{lb}{year}}{1{,}085.6\frac{\text{lb}}{\text{yeay}}}\right] \times 100\% = [0.6994] \times 100\%$$

$$= \mathbf{70}\%$$

Annex III: Ground-based GPS points collected from study areas

GPS points from the Hareko and Messebo tabias of seven sand and gravel production sites were collected. The data used to link field observations with GIS and remote sensing data, supporting land use and land cover mapping for farmland, bushland, and bareland (2005–2025). The data showed that raw material sources were on hillsides with bushland and honeybee flora (mainly Acacia), some previously conserved but now degraded. Crusher and campsite facilities on farmland caused dust, sedimentation, and unmanaged by-product pollution, affecting upstream farmland and livestock grazing areas. Bushland was heavily damaged, including highly eroded and previously treated hillsides, while downstream areas and nearby settlements suffered from runoff and sediments.

Site-level collected Ground GPS points			Description
Latitude	Longitude	Altitude (m) a.s.l	
13∘ 16′ 22.79″ N	39∘ 22′ 08.60″ E	2561.2	The hillside of the raw material source is embedded within bushland and is highly dominated by honeybee flora.
13∘ 16′ 24.32″ N	39∘ 22′ 08.53″ E	2559.3	Crusher and campsite facilities are installed over farmland.
13∘ 16′ 24.23″ N	39∘ 22′ 06.75″ E	2597.1	The hillside of the source area is highly dominated by bushland and various native tree species.
13∘ 16′ 25.45″ N	39∘ 22′ 08.18″ E	2563.3	Useful materials and by-products are generated from the extraction activities.
13∘ 16′ 23.60″ N	39∘ 22′ 10.16″ E	2551.7	Farmland located downstream of the crusher is negatively affected.
13∘ 16′ 20.40″ N	39∘ 22′ 11.26′ E	2553.1	Affected farmland areas are observed in the vicinity of the site.
13∘ 16′ 29.36″ N	39∘ 22′ 07.70″ E	2554.7	An illegal by-product dumping site is located below the main road connecting to Hintalo town.
13∘ 16′ 26.98″ N	39∘ 22′ 09.33″ E	2558.0	Livestock grazing land in the surrounding area is affected.
13∘ 16′ 26.04″ N	39∘ 22′ 06.93″ E	2590.5	The source area is disturbed and lacks treatment, rehabilitation, or mitigation measures.
13∘ 16′ 25.33″ N	39∘ 22′ 05.55″ E	2649.3	Surrounding bushland is affected by dust emissions from crusher operations.
13∘ 16′ 32.92″ N	39∘ 22′ 13.85″ E	2522.7	Farmland is highly affected by dust particles generated from crusher operations.
13∘ 16′ 29.67″ N	39∘ 22′ 12.02″ E	2538.2	The downstream area of the crushers is exposed to sedimentation resulting from on-site and off-site soil erosion.
13∘ 16′ 41.38″ N	39∘ 22′ 09.96″ E	2559.3	The excavated raw material extraction areas, which lack conservation measures, have developed into gully and gorge formations that collect surface runoff during the rainy season.

Annex IV: Monthly and annual revenue from sand and gravel sales, excluding informal trade elsewhere.

Parameters	Monthly and annual revenue from Sand and Gravel Sales in the three trading centers of Mekelle City					
	Monthly			Yearly		
	Manufactured Sand	Manufactured Gravel	Total	Manufactured Sand	Manufactured Gravel	Total
Monthly operations						
Estimated Truckloads	5	7	12	50	70	120
Average estimated annual truckload unit price (Birr)	29,670	40,560	-	29,670	40,560	-
Total Purchasing Cost (Birr) per year	148,350	283,920	432,270	1,483,500	2,839,200	4,322,700
Truckload Selling Price (Birr)	49,180	58,181	-	49,180	58,181	-
Total Sales (Birr)	245,900	407,267	653,167	2,459,000	4,072,670	6,531,670
Labor Analysis						
Estimated daily laborers			18		180	180
Average estimated active yearly working days			13		130	130
Average Daily Wage payment			800		800	800
Total estimated earnings (Birr)			187,200		18,720,000	187,200
Monthly Tax Payment (Birr)			6750	Yearly Tax Payment (Birr)		81,000
Total labor and tax cost			193,950	Total labor and tax cost		268,200
Total expense			626,220	Total expense		4,590,900
Total sales			653,167	Total sales		6,531,670
Total profit per Year			26,947	Total profit per Year		1,940,770
Total revenue per 3 sites/Year			8,982.3	Total profit per 3 sites/Year		646,923.33

Source: Survey data,202

Annex V: LCI parameters, unit measures, measurement methods, and references

S/n	Parameter	Unit measures	Reviewed secondary documents	Sources
1	Diesel fuel consumption	L/year	On-site operational logs of loaders, trucks, and excavators	Üçtuğ et al., 2025
2	Electricity consumption	kWh/year	Meter readings of crushers, screens, and conveyors	
3	Freshwater for dust suppression	m^3/year	Measured on-site; calculated per EN 15804+A2 by dividing total water use by annual production mass	Üçtuğ et al., 2025 EN 15804+A2
4	Material throughput	t/year	Annual production volume × bulk density (1.6 t/m^3)	Üçtuğ et al., 2025
5	Emission factors	kg CO_2-eq/unit	IPCC emission factors applied to fuel and electricity use	Eggleston et al., 2006
6	Process efficiency improvements	%	Literature case study on pre-screening before crushing	DA, 2025

Annex VI: Methodologies and assumption justification

Keywords from the methodologies used	Assumption justification
Sample size and representativeness	The quarry sites and the 80 respondents were considered representative of typical sand and gravel extraction activities in the study region.
Reliability of Primary Data	Information collected from questionnaires, interviews, field observations, and on-site measurements was assumed to reflect actual practices.
Applicability of secondary data	Emission factors, operational standards, and climatic data from IPCC, USEPA, EN 15804+A2, and other references are assumed to be relevant to the study context.
Consistent operations days and hours	Daily working hours, annual working days, crusher types and efficiency, and material properties such as bulk density were assumed to remain stable during the study period.
Defined system boundaries and exclusions	The study covers cradle-to-gate processes (Modules A1–A3); preparation for use (A4–A5), use-phase (B1–B7), end-of-life (C1–C4), and recycling (D1) modules were excluded due to inconsistent data across the system boundary.
Completeness of flows	All material and energy inputs and outputs crossing the system boundary were assumed to have been fully recorded and documented.
Standard calculation methods	Simple arithmetic formulas, EN 15804+A2 guidelines, and well-to-wheel diesel emission factors are assumed to provide accurate estimates of emissions, water use, and production efficiency.
Environmental and socio-economic consistency	Observed environmental and socio-economic conditions at study sites and selected urban sampling points are assumed to reflect typical rural–urban interactions.

Annex VII: Negative social impacts and the status of mitigation measures

Identified key social mitigation measures	Planned mitigation measures	Observed current status	Mitigation measures effectiveness in addressing the problems	Mitigation measures Limitations	Supporting Studies from other areas
Payment for leased farmland	Compensate farmers for land lost to extraction	Provided to 29 farmers a total of 12,083,333 Birr; avg 96,667 Birr per person	Provided short-term financial relief; 87% of households compensated	Did not reflect long-term land value; 17% households remained vulnerable; appeals were ignored	Abera (2020); Saleem & Ayalew (2025)
Fertilizer support	Offset productivity losses due to dust and soil degradation	Provided to 6 farmers at 50 kg/person/year	Offered short-term relief; helped maintain annual production	Did not address structural soil fertility decline; limited long-term effectiveness	Belay et al. (2020); Hemmler et al. (2024); Zhao et al. (2025)
Infrastructure development (e.g., church, electricity)	Support community cohesion and welfare	Only one investor constructed a church and installed electricity	Strengthened social cohesion and access to services	Rarely applied by other investors; profit prioritized over community support	Abera (2020)
Health and welfare support	Contribute ≥200,000 Birr/year per crusher for vulnerable households	Only 4 of 7 crushers (57%) participated; support is insufficient	Provided partial assistance to some vulnerable households	Weak monitoring and enforcement; inconsistent delivery	Saleem & Ayalew (2025); Weldeamanuel & Cheng (2024)
Community consultation and grievance response	Ensure participatory decision-making and dispute resolution	Limited or absent; communal land leased without prior consultation	Low community trust; unresolved disputes heightened tensions	Weak governance; authorities unresponsive to grievances	Abera (2020); Weldeamanuel & Cheng (2024)
Employment opportunities	Provide local jobs during extraction	Tied exclusively to active extraction phases	Temporary livelihood support	Did not extend beyond the extraction phase; limited skill-building or long-term benefit	Abera (2020); Saleem & Ayalew (2025)
Integration with environmental measures	Link social support to rehabilitation and dust mitigation	Largely absent	Could enhance resilience and livelihoods if implemented	Missed opportunity for long-term socio-environmental benefits	Saleem & Ayalew (2025); Weldeamanuel & Cheng (2024)

Sources: Survey result, 2025