



*Addis Ababa University*  
*Addis Ababa Institute of Technology*



**ADDIS ABABA UNIVERSITY**

**Addis Ababa Institute of Technology**

**Center for Ethio Mines Development**

**Master of Engineering in Mineral Engineering**

**TITLE: - “EVALUATION OF BORAX AS AN ALTERNATIVE TO MERCURY IN GOLD RECOVERY:  
A CASE STUDY OF BENISHANGUL GUMUZ REGION, ASSOSA AREA, WESTERN ETHIOPIA”**

**By Zeryihun Hailu Gebremariam**

**A Graduate Project Work submitted to the Center for Ethio–Mines  
Development in partial fulfillment of the requirements for the degree of  
Master of Engineering in Mineral Engineering.**

**May/2025**

**Addis Ababa, Ethiopia**

**ADDIS ABABA UNIVERSITY**  
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**Evaluation of Borax as an Alternative to Mercury in Gold Recovery: A Case Study of Benishangul Gumuz Region, Assosa Area, Western Ethiopia**

**By Zeryhin Hailu Gebremariam**

**Advisor: Bisrat Kebede (pHD)**

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**A Graduate Project Work submitted to the Center for Ethio-Mines Development in partial fulfillment of the requirements for the degree of Master of Engineering in Mineral Engineering.**

**May/2025**

**Addis Ababa, Ethiopia**

**Declaration of Originality**

This is to certify that I, Zeryihun Hailu Gebremariam, have carried out the project work entitled "Evaluation of Borax as an Alternative to Mercury in Gold Recovery: Case Study of Benishangul Gumuz Region, Assosa area, Western Ethiopia" as a partial fulfillment of master's degree. The work has been done by the guidance of my advisor, Bisrat Kebede (phD) from the Mineral Industry Development Institute and Enatfanta Melaku (MSc.) as my co-advisor also with the Mineral Industry Development Institute.

I declare that this dissertation has not been submitted in whole or in part for consideration towards any other degree, diploma or other similar award of any university or institution.

Moreover, I also ensure that this work has never appeared elsewhere and that both published and unpublished sources have been acknowledged and cited accordingly.

Signature

Date

Zeryihun Hailu Gebremariam

\_\_\_\_\_

\_\_\_\_\_

Under my supervision, the candidate undertook the above-mentioned project. As far as I am concerned, the work is original and has been submitted in partial fulfillment of the requirements for the degree of master.

Signature

Date

Dr. Bisrat Kebede (Advisor)

\_\_\_\_\_

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Signature

Date

Enatfanta Melaku (Co-advisor)

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We certify that the project work entitled “Evaluation of Borax as an Alternative to Mercury in Gold Recovery: A Case Study of Benishangul Gumuz Region, Assosa Area, Western Ethiopia” pursued by Zeryihun Hailu Gebremariam is carried out and submitted in partial fulfillment for the degree of Master of Engineering in Mineral Engineering, satisfies all the regulations of the University and is accepted as per the regulations of the University with respect to originality and Quality.

**Approved by advisors and examiner:**

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## **Abstract**

Artisanal and small-scale gold mining (ASGM) plays a critical role in the Ethiopian economy, particularly in rural and resource-endowed regions like the Benishangul Gumuz Region, where it forms a mainstay of livelihood for many households. However, the extensive use of mercury for gold recovery in ASGM operations has raised serious environmental and public health concerns, such as soil and water contamination and toxic exposure that affect not only miners but also adjoining communities. The goal of this study was to evaluate borax as a safer and more environmentally friendly alternative to mercury in the gold extraction process, with a focus on the Assosa Zone. The study adopted comparative experimental analysis with ore samples collected from two geologically different mining areas: Agosha Kebele (quartz-vein-hosted primary ores) and Mukufute Kebele (alluvial placer deposits). Through the adoption of borax smelting and conventional mercury amalgamation techniques, the effectiveness of gold recovery was analyzed using statistical methods, including descriptive analysis, Wilcoxon Signed-Rank tests, and ANOVA. The results revealed that borax smelting yielded significantly better gold yields, with a mean recovery of 0.6125 g, compared to 0.2345 g from mercury amalgamation, while at the same time avoiding the toxic emissions and residual pollution associated with mercury. Borax also proved versatile for both ore types and showed practical advantages regarding safety, cost-effectiveness, and environmental preservation. This study confirms the technical and economic viability of introducing borax in Ethiopia's ASGM industry and informs the wider effort towards reducing mercury use in small-scale mining. The study concludes by advocating for the adoption of borax through policy support, stakeholder training, and awareness creation, while also proposing areas of future research to determine its long-term environmental effects, socio-cultural acceptability, and potential for scalability in other mining areas.

Keywords: Borax, Mercury-Free Gold Recovery, Artisanal Mining.

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## **Glossary of Abbreviations**

ANOVA	Analysis of Variance
ASGM	Artisanal and Small-scale Gold Mining
Au	Gold
BCE	Before Common Era
BGR	Benishangul Gumuz Region
CDF	Cumulative distribution function.
ECDF	Empirical cumulative distribution function
g	Gram
GBMs	Gravity Based Methods
GDP	Gross Domestic Product
H <sub>0</sub>	Null Hypothesis
H <sub>1</sub>	Alternative Hypothesis
Hg	Mercury
IQR	Interquartile range.
NANS	Neoproterozoic Arabian-Nubian Shield
NGOs	Non-Governmental Organizations
SNNPR	Southern Nations, Nationalities and Peoples Region
StDev	Standard Deviation
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
WHO	World Health Organization

## Chapter 1

### Introduction

#### 1.1 Background

Ethiopia depends heavily on gold mining as it contributes to export earnings, generating jobs and national revenue. The mining sector approximately contributes with 1% to the national GDP, where gold is the dominant contributor to the growth of this sector (Hailu Elias and Atlaw Alemu, 2022).

Artisanal and small scale gold mining (ASGM) is important in the sector and accounts for majority of the gold in the country (Selam Tariku, 2021). These activities are essential for the livelihoods of millions of people, especially in rural areas such as the Benishangul Gumuz region where there are few opportunities for other forms of economic activity (Degfie Teku, 2025).

Although it has the potential to contribute greatly to the economy, artisanal and small-scale gold mining is also largely inefficient, informal and associated with environmental and public health risks. The intensive use of mercury for gold extraction, in particular, has caused significant socio-environmental impacts, highlighting the urgent need for the implementation of more sustainable and safer mining activities (Hilson & Pardie, 2006).

The Assosa Zone of the Benishangul Gumuz region is known for its abundant gold deposits, which are primarily mined through ASGM. Mining remains critical to the local economies in this region, generating income and trade for hundreds of thousands of households (Bullock and Morgan, 2018). With crude methods of panning and amalgamation using mercury, both labor intensive and environmentally hazardous, used by the miners.

The mercury amalgamation remains the most common technique of gold extractions used in artisanal small-scale gold mining (ASGM), especially in developing countries, despite its highly destructive impacts on both environmental sustainability and human health (Hilson & Pardie, 2006). The technique releases toxic mercury vapors into the air and contaminates water, soil, and aquatic life, resulting in lasting ecological devastation (Driscoll et al., 2013). The negative impacts of mercury exposure, especially on children and pregnant women, include neurological impairments, reproductive factors, and chronic diseases (Gibb & O'Leary, 2014). Additionally,

mercury poisoning negatively impacts agriculture, as well as biodiversity, resulting in sustainability issues in mining communities (Hilson & Pardie, 2006). Despite international initiatives, including the Minamata Convention, to eradicate mercury utilization, the majority of local populations still adopt unsafe practices due to technical, social, and economic limitations (Gibb & O'Leary, 2014).

Specifically, in Ethiopia, particularly in the Benishangul Gumuz Region, the negative consequences of mercury utilization have induced hazardous environmental degradation and health crises rather than economic growth (Yohannes Gelaye, 2022). Lesser known International treaties that promote reduction of mercury use among small scale miners can only be properly adhered to when local miners are knowledgeable, adequately resourced and can have these treaties regulated.

The utilization of borax for artisanal and small-scale gold mining (ASGM) is responsible for reduced melting points in gold-bearing minerals, thus increased extraction from contaminants while substantially reduced associated health and environmental risk. Both the Philippines and Tanzania have utilized the use of borax very successfully, recording recovery efficiency levels greater than, traditional mercury intensive processes. (Appel & Na-Oy, 2014; Appel & Veiga, 2012).

Despite its promising potential as a novel technique of gold processing, its implementation in Ethiopia is currently limited, owing mostly to a lack of complete studies that have evaluated its effectiveness in Ethiopia's distinctive geologic as well as socio-economic settings. In a move to fill this gap, this study assesses the technical, environmental, as well as socio-economic feasibility of using borax to extract gold in the Benishangul Gumuz Region, hence propelling further development of more environment-friendly as well as responsible mining practices.

## **1.2 Research Problem**

Artisanal and small- scale gold mining (ASGM) is a main livelihood exertion for utmost people in the Benishangul Gumuz Region of Ethiopia. The main method used for gold extraction is still mercury amalgamation owing to its efficiency in trapping fine gold particles, thus enabling their recovery. However, the method presents high environmental and health hazards. The emission of

mercury vapor during the heating process, as well as residual mercury, pollutes terrestrial and aquatic environments, leading to long-term pollution that causes extreme health hazards, such as neurological and renal complications (Gibb and O’Leary, 2014; Driscoll et al., 2013).

As a response to these threats, Ethiopia committed to reducing its mercury use progressively by signing up to the Minamata Convention on Mercury, where a formal reduction or phasing-out of mercury in ASGM and small-scale mining is encouraged. The persistent use of mercury, however, can be explained by a lack of scientifically validated, context-adequate alternatives (UNEP, 2013).

Sodium borate, also known as borax, has been suggested as an effective yet non-toxic mercury substitute. The compound acts as a flux, lowering the melting point of gold, hence enabling efficient recovery of valuable metals from impurities (Appel and Na-Oy, 2013). However, its applicability in practice in Ethiopia is not well defined, owing to a lack of scientific studies focusing on the country-specific geology and metallurgical properties.

Optimization and stabilization of the process is the most important point but the overall gold recovery is depended on some crucial parameters. The mineralogy of the ore, specifically the presence of sulfide minerals such as pyrite and arsenopyrite, greatly impacts the effectiveness of the borax method since these minerals may encapsulate fine gold and inhibit its recovery (Appel & Na-Oy, 2012). In addition, the presence, proportion, and amount of gangue materials mainly clay, silicate, and carbonaceous substances impact the smelting process and the effectiveness of gold separation (Appel and Na-Oy, 2014). Additionally, regional geological environment differences, for example, the distinction between quartz-vein-hosted primary ores and alluvial placer deposits, result in variations in ore textures, particle size, and impurity levels, all of which influence the effectiveness of the borax process (Appel & Na-Oy, 2014; Hilson & Pardie, 2006; Spiegel & Veiga, 2010).

The unique challenge of ores as well as geologic conditions necessitates focused research to determine relevance and limitation of using borax during gold processing in relation to Ethiopia. Without empirical evidence dealing with local ore characteristics, calling upon using borax has no scientific basis. Therefore, this study focuses on filling this gap by objectively assessing

technical effectiveness of using borax relative to local ore types, mineral compositions, and geologic settings in the Benishangul Gumuz Region.

### **1.3 Research Rationale**

The uses of mercury in ASGM in the Benishangul Gumuz Region bring pressing environmental, health, and socio-economic issues that warrant consideration of safer alternatives, such as borax. Mercury toxicity has enormous potential range and its severity, but it is possible to avoid these consequences using non-toxic alternatives (Bose-O'Reilly et al., 2010). Borax offers a solution for potential such issues and has proven successful in other countries (Appel & Na-Oy, 2014) by reducing risk through reduced exposure and promoting the mining process in a less polluting manner.

Borax usage leads to health benefits, but it also has important environmental dividends. Gold extraction by borax reduces mercury pollution in water and soil and can assist in making mining villages that depend on these resources sustainable in the long term. The economic potential involved in phasing mercury out in favor of borax in artisanal gold mining is significant. Borax also acts as a cheaper, more readily available alternative in many areas, thus presenting artisanal miners with an economically viable alternative that can boost rates of gold recovery without compromising on international environmental standards (Appel & Na-Oy, 2014; Appel and Jønsson 2010; Køster-Rasmussen et al., 2015). By making available to miners access to green technology, such as methods of extraction using borax, further, mercury usage has a potential to be eliminated, enhancing both economic well-being and environmental sustainability among mining communities.

### **1.4 Research Objectives**

#### **General Objective**

The overall purpose of this study was to investigate the potential of replacing mercury with borax as a gold recovery agent in the artisanal and small-scale mining sector of the Benishangul Gumuz Region, Ethiopia.

### **Specific Objectives**

- To investigate the efficiency of borax for gold recovery relative to mercury.
- To assess the variability and consistency of gold recovery results obtained through borax smelting across different ore types (quartz-vein-hosted primary ores and alluvial placer deposits).
- To evaluate the suitability of borax smelting in various geological settings in the Benishangul Gumuz Region.
- To provide statistical evidence supporting the feasibility and reliability of borax smelting as a standard gold recovery method in artisanal mining.
- Compare the environmental impact of using borax versus mercury in local mining practices.

### **1.5 Research Questions**

1. What is the comparative efficiency of borax versus mercury in gold recovery within artisanal and small-scale mining operations in the Benishangul Gumuz Region?
2. How consistent and variable are the gold recovery results obtained using borax smelting across different ore types, including quartz-vein-hosted primary ores and alluvial placer deposits?
3. To what extent is borax smelting suitable for gold recovery in the diverse geological settings of the Benishangul Gumuz Region?
4. What statistical evidence supports the feasibility and reliability of borax smelting as a standard method for artisanal gold recovery?
5. How do the environmental impacts of borax-based gold recovery compare to those associated with mercury use in local mining practices?

### **1.6 Significance of the Study**

This study promises to address very important environmental, health, and socio-economic problems surrounding artisanal and small-scale gold mining (ASGM) in Ethiopia. The question of whether or not to adopt borax in place of mercury for gold recovery has ramifications for environmental conservancy, human health, and policymaking.

**Environmental Conservation**

Mercury is well-known as a toxic pollutant which represents a long-term ecological and human health risk by contaminating soil, water and air (Driscoll et al., 2013). Borax can be used as a non-toxic and eco-friendly option to offset mercury emissions and contaminations in Benishangul Gumuz Region. This evolution aims to do what global initiatives like the Minamata Convention on Mercury intends to do; eliminate or significantly reduce environmental geochemical degradation caused by Artisanal Small-Scale Gold Mining (ASGM) activities (UNEP, 2013). This study helps promote biodiversity and maintain sustainability of local ecosystems that are essential for agriculture and water supply in the region, by minimizing environmental pollution.

**Health Improvements**

Mercury exposure has serious implications for human health causing neurological disorders, reproductive and developmental damages, especially in miners and the surrounding population (Bose-O'Reilly et al., 2010). By replacing mercury with borax in gold recovery methods, miners will have eliminated both direct and indirect mercury exposure, thus protecting themselves, their families and those living downstream. This study provides empirical evidence on the advantages of borax which is essential to facilitate safer mining that improves public health and reduces healthcare obligations in the mining communities.

**Policy Formulation**

These findings will be instrumental for the policymakers and stakeholders who are seeking to regulate ASGM practices within the country. That would illuminate the extent to which borax is valid as a replacement for mercury in gold extraction and how penetrative borax is into the mining sector, information that will guide policies to reduce mercury and to promote sustainable mining practices. This provides environmental & public health policy context to mining in Ethiopia, outlier inertia to international conventions and standards (Spiegel & Veiga, 2010). This study shows that mercury free gold recovery is feasible and can be a model for other places with some problem.

## 1.7 Scope and Limitations

This study specifically assesses the potential for borax to replace mercury used in artisanal and small-scale Gold mining (ASGM) practices within the Benishangul Gumuz Region in the West of Ethiopia, with a focus on the Assosa Zone. This area contains the largest gold deposits of the country and ASGM operations that utilize mercury in abundance. By focusing the investigation on this geographical and socio-economical context, the study aims to assess the technical feasibility, environmental impacts and socio-economic implications of instituting borax in local gold recovery practices.

This study has several limitations although it can contribute to knowledge. First, resource constraints such as, limited financial and logistical resources can limit the extent of field data collection and field experiments. The access to equipment and materials needed to test the efficacy of borax versus mercury may also be limited, thereby affecting the scope of the study.

In the region, many artisanal miners have been using mercury for decades because it is cheap, known, and good at recovering gold. This dependency on mercury creates hurdles in the advancement of borax usage, regardless of its benefits being proven.

Finally, the results of this study may show regional specificity since geological background, composition of ores and socio-economic circumstances differ between regions. In addition, it should be noted that the geological properties of the Benishangul Gumuz Region may have or not an effect on the effectiveness of the borax as a processing agent, leading to the impossibility of generalizing the results in this study to other mining areas. It also should be noted that socio-economic dynamics such as miners' education levels and access to alternative technologies may constrain the extent to which findings can be generalized to wider contexts ([Getnet Belachew, 2023](#); [Misganu Kabeta et al., 2024](#)).

Recognizing the aforementioned limitations, this study emphasizes the need for ongoing research in other mining contexts and larger-scale studies that can validate and/or broaden observed patterns.

## Chapter 2

### Literature Review

#### 2.1 Overview of Gold Recovery Methods

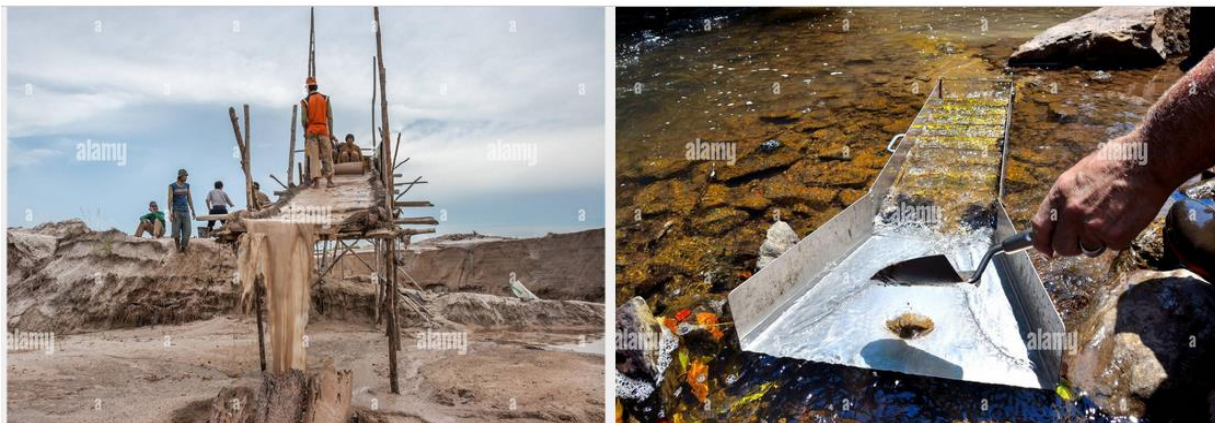
##### 2.1.1 Historical Background:

#### Gold Recovery: Evolving Processes, from Ancient to Modern

Since the ancient times, methods of recovering gold have undergone a change over the centuries, thanks to technological, environmental, and economic considerations. Gold recovery methods in ancient times were fundamentally mechanical processes that took advantage of differences in density between gold and other materials, namely panning and sluicing. However, those methods were very labor-intensive, often producing small quantities of gold. We know from historical records that such techniques have existed at least since 3000 BCE, in ancient Egypt and Mesopotamia, where gold was already appreciated for its aesthetic and cultural value (Hinton et al., 2003).

#### Gravity Based Methods (GBMs) Used Early On

Gravity separation is one of the old gold recovery processes. Methods like panning where swirling water with sediment in a pan to wash away everything else but gold and sluicing where a sloped trough traps heavier gold particle were common.



**Fig: 2.1 Sluicing box types** (Source: [Alamy Stock Photo](#))

By applying these methods, gold, with a sharp density contrast ( $19.3 \text{ g/cm}^3$ ), could be separated

from sand and gravel which had lower densities (Veiga et al., 2006). Though highly successful in extracting larger fragments of gold, such methods could not facilitate fine recovery of gold so upgrades on techniques were needed.

### 2.1.2 Current Techniques

#### Mercury Amalgamation

Mercury amalgamation is a common method used in small-scale mining due to the fact that it is easy and cheap. Mercury amalgamation involves the combination of mercury with ore that contains gold to form an amalgam. The amalgam is then heated so that the mercury is burned away and the gold is left behind. As mercury has the ability to bond with gold particles, they are used to recover gold from low grade ores (Spiegel & Veiga, 2010). But mercury can harm the environment and health to a great extent. When miners heat it, they breathe in poisonous mercury vapor, and when mercury gets into water, it pollutes the ecosystem of the fish and other aquatic life, causing it to build up in the food chain (Cordy et al., 2011).

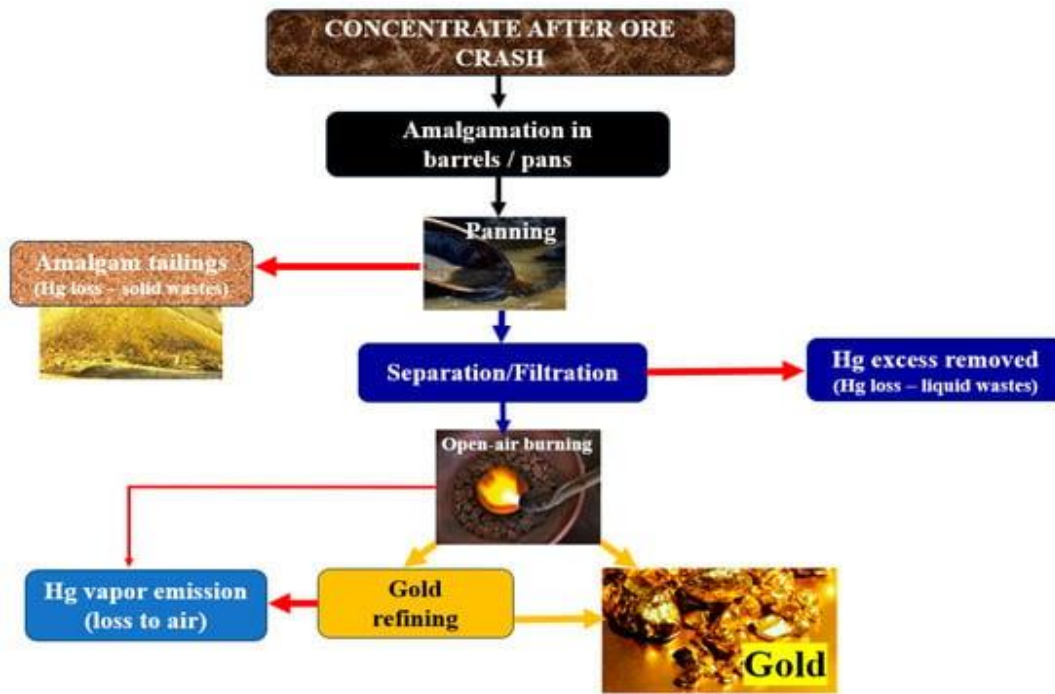
**Table 2.1: National Gold Production from Major Production Areas (2014)**

S. No.	Region	Gram/person per month (a)	Total Population involved (b)	Quantity Produced by Artisanal (Kg): a x b x 6 Months
1	Oromia	2.3	650,200.00	8,972.76
2	BGR	1.6	110,950.00	1,065.12
3	SNNPR	2.8	320,100.00	5,377.68
4	Tigray	2.7	160,000.00	2,592.00
	Total Gold		<b>1,241,250.00</b>	

(Source: Ministry of Mines and Petroleum, 2020).

Artisanal and small-scale gold mining (ASGM) is fundamental to gold production, with the majority of it occurring in areas such as Oromia, Benishangul Gumuz, SNNPR and Tigray. It provides a significant number of job opportunities and is a basic source of rural livelihood while contributing to the national economy at the same time. However, against the backdrop of its economic role, the use of traditional and often hazardous gold extraction methods raises an acute need for the use of safer and more sustainable harvesting methods, which would improve miners'

health and protect the environment.



**Figure 2.2: Flow chart of the typical amalgamation process used in developing nations by small scale miners in artisanal gold mining.** (Source: Donkor et al., 2024)

The red arrows indicate the quartz-vein-hosted primary ores points where mercury is released into various environmental compartments (Donkor et al., 2024)

### Cyanidation

Cyanidation is applied on a large scale in large mining companies to recover gold since it suits large quantities of ore. Cyanidation involves dissolving gold in a cyanide solution and recovering it by processes such as carbon adsorption or zinc precipitation (Yannopoulos, 1991). Though efficient, cyanidation is not usually used in ASGM because it is complicated, expensive, and can be detrimental to the environment. There is the chance for cyanide leaks that totally destroy local ecosystems (Veiga et al., 2014).

### Gravity Separation

Modern gravity operations including sluice use, jigging, and shaking tables have taken over conventional operations with a high gold yield and loss minimization. Gravity operations work

best for gold particles that are coarse and have widespread use in ASGM for ease and at a low cost (Hilson & Pardie, 2006). Gravity operations have a reduced effectiveness for fine gold particles, and most of them become loss during processing.

### **Flotation**

Sulfide ores are generally used for flotation in industrial minerals mining to recover gold. In the process, chemicals are mixed with slurry of ground ore, which enables gold and sulfide minerals to stick to air bubbles and float to the surface where they can be collected (Dunne, 2016). Flotation, despite its efficiency, is a sophisticated technology and technology intensive practice, and therefore not accessible for most ASGM operators (Özçelik & Ekmekçi, 2024).

### **2.1.3 Emerging Technologies**

#### **Introduction of Eco-Friendly and Innovative Methods**

In response to environment and health concerns over mercury and cyanide, environmentally friendly gold extraction processes have become increasingly important in recent years. One of them is sodium borate, more commonly known as Borax ( $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ), a safer and equally efficient approach for gold recovery compared to mercury. This structure of borax ( $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ) allows it to be a great flux during gold recoveries as it reduces the melting point of gold and assists in removing impurities. As a result, it is possible to isolate gold without the toxic emissions generated from the use of mercury (Appel & Na-Oy, 2014). Laboratory and field tests are presented to show the potential for using borax in ASGM, in particular for fine gold recovery.

#### **Examples from Regions Transitioning from Mercury Use**

Certain areas have changed from mercury based gold recovery systems to borax. For example, a mercury free gold mining initiative has provided small scale miners in the Philippines with training on borax use, resulting in similar recovery percentages compared to those achieved with mercury and a large decrease in health risks (Appel & Na-Oy, 2012). Relatedly, it has highlighted the competitive and environmental advantages of borax which would support the adoption of borax amongst artisanal miners, as noted by studies based on Tanzania and the Amazon region (Veiga et al., 2014). These examples illustrate the potential of borax to

revolutionize ASGM practices and render them consistent with global sustainability objectives such as the Minamata Convention on Mercury (UNEP, 2013).

## **2.2 Environmental and Health Impacts of Mercury**

### **2.2.1 Environmental Impacts**

Mercury is highly persistent and toxic heavy metal, and it causes serious damage to the environment. In artisanal and small-scale gold mining (ASGM), direct discharge of mercury in atmosphere, water, and soil takes place during amalgamating stage. Inadequate disposal of residues of mercury creates widespread contamination in surrounding environments with long term environment and health consequences (Driscoll et al., 2013).

#### **Mercury Contamination in Soil, Water, and Air**

Mercury emitted during the extraction of gold contaminates the soil in mining regions, affecting their fertility and making them unsuitable for agricultural use. The water bodies contaminated with mercury act as sinks where it enters aquatic organisms and ultimately impacts the communities that depend on them for drinking and irrigation purposes (Driscoll et al. 2013). Burning amalgam to extract gold cause atmospheric emissions of mercury that can be transported great distances, deposited in surrounding environments and make mercury a global pollutant (Telmer & Veiga, 2009).

#### **Bioaccumulation and Biomagnification in Aquatic Ecosystems**

Mercury enters aquatic ecosystems as inorganic mercury which is converted to methylmercury through microbial activity. Methylmercury is extremely toxic and can bioaccumulate in aquatic organisms, resulting in biomagnification up the food chain. Such processes are particularly risky for predators, including humans, that organically reside at higher levels of food webs, such as through the consumption of contaminated fish and other aquatic resources (Rodrigues et al., 2019).

#### **Mercury Flour Formation**

Gold recovery with mercury introduces another environmental contamination challenge with the production of mercury flour. This happens in the milling process, in which hard metal rods or

balls pound mercury repeatedly to produce tiny mercury droplets less than a millimeter in size. The droplets, which are known as mercury flour, do not coalesce and are distributed throughout the milled gold ore, which is not retrievable by miners, but leads to even greater environmental contamination when washed away with tailings (Appel & Na-Oy, 2014).



**Fig 2.3: Milled gold ore with mercury flour** (Source: Appel & Na-Oy, 2014).

As depicted in Figure 2:3 above, mercury flour is dispersed throughout milled gold ore and there is an urgent requirement for alternative recovery methods that avoid such environmental degradation.

### **Case Studies of Mercury Pollution in Artisanal Mining Regions, Including Ethiopia**

Studies have documented disastrous consequences of mercury pollution in communities involved in ASGM globally. In Colombia, gold mining through artisanal mining produced the largest per capita emissions in the world (Cordy et al., 2011). In Indonesia and Ghana, mining areas have seen high concentrations of mercury over safe levels of the World Health Organization (WHO), with a general environment and a state of epidemic in a healthy state (Obiri-Yeboah et al., 2021; Paruchuri et al., 2010)). In Ethiopia, in the Benishangul Gumuz region, mercury has been at the origin of contaminated water and agricultural productivity, and safer alternatives become a matter of urgency.

### 2.2.2 Health Impacts

The chemical element mercury (Hg) is responsible for environmental pollution and human exposure through the inhalation of vapor during amalgam burning, ingestion of contaminated water and food, and skin contact during mining. Inhalation is especially damaging because vaporized mercury directly enters the bloodstream leading to systemic toxicity (Clarkson, 2006; Wu et al., 2024; Gibb and O’Leary, 2014).

Health problems are associated to mercury poisoning. Symptoms include neurological, such as tremors, loss of memory, and impairment in cognitive function. Long term exposure can also cause developmental problems and permanent nervous system damage, especially in children (Bose-O’Reilly et al., 2010). Mercury is further implicated in reproductive health, resulting in miscarriages and birth defects (Henriques et al., 2019; Kumar et al., 2022).

Mercury toxicity is most vulnerable in pregnant women and children whose neurological development is in its formative stage. Some communities directly engaged in ASGM may be at elevated risk as they are frequently in direct contact with mercury bearing environments on a day to day basis (Gibb & O’Leary, 2014). Exposure in such groups to mercury has been responsible for extreme consequences, including a shorter life span and compromised life quality (Obiri-Yeboah et al., 2021; Paruchuri et al., 2010).

### 2.2.3 Global Initiatives to Address Mercury Use

International efforts to mitigate the use of toxic chemicals like mercury in artisanal and small scale gold mining (ASGM) seek to minimize its impact on the environment and health and promote environmentally friendly techniques.

#### **Overview of the Minamata Convention on Mercury**

The Minamata Convention, which was adopted in 2013, is an international treaty to protect human health and the environment from mercury. It contains provisions for the gradual elimination of mercury use in ASGM through the promotion of alternatives, such as borax, and the establishment of guidelines for safe mercury handling. The convention also requires member states to establish national action plans to address mercury pollution, including from artisanal

mining in their communities (UNEP, 2013).

### **International Efforts to Phase out Mercury in ASGM**

Many programs have been developed to promote mercury free gold mining. Agencies such as the United Nations Industrial Development Organization (UNIDO) and the United Nations Environment Program (UNEP) have facilitated through new technology and training miners in safer working techniques (Veiga et al., 2014). Successful case studies in other countries around the world, such as the Philippines and Mongolia, illustrate that mercury free gold recovery is possible, for example by using a borax method, and indicate that the transition to mercury free gold processing can be viable in other national contexts as well, including Ethiopia (Appel & Na-Oy, 2012).

## **2.3 Role of Borax in Gold Recovery**

### **2.3.1 Mechanism of Borax in Gold Recovery**

Borax or sodium borate, if we are being technical, has special properties that make it a useful component for recovering gold, especially in small scale mining operations. One of its important traits is that it reduces the melting point of metallic gold and oxides of metal, which assists in separating gold from ore and other impurities. In the smelting process, borax functions like a flux; as part of this reaction, a borate glass is formed, which captures nonmetallic impurities but allows the molten gold to sink to the bottom of the crucible (Veiga et al., 2014).

The processing of gold ore involves crushing, treatment with chemicals, melting (smelting) and further purification. The ore powder is mixed with borax and then melted in a furnace. Borax interacts with silicate impurities to create a glassy slag during smelting and fuses pure gold. Borax acts in purely physical and chemical ways, while mercury amalgamates with gold through a harmful chemical reaction. In this case, mercury poisons the by products produced when gold is extracted (Appel & Na-Oy, 2012; 2014).

### **2.3.2 Advantages of Borax over Mercury**

Using borax over mercury in artisanal and small-scale gold mining (ASGM) is healthy, cost effective, and environmentally friendly in numerous ways:

**Non-Toxic and Environmentally Safe**

Borax is safe and does not endanger miners, local communities or the ecosystem. In contrast, mercury accumulates in the environment and contaminates water food chains, but borax is readily soluble in water and has few environmental impacts (Appel & Na-Oy, 2014).

**Cost Effectiveness and Availability**

Borax can be found in many mining regions and is cheaper than mercury. It is a cost effective alternative for artisanal miners with little working capital (Hilson & Pardie, 2006).

**Higher Recovery Rates in Certain Contexts**

Under certain geological conditions, the gold can be recovered effectively and even better with borax than using mercury. When ores can be smelted, the use of borax can lead to higher yield of gold with much less waste (Veiga et al., 2006).

**2.3.3 Challenges in Adopting Borax**

While borax has benefits, there are still lots of obstacles to using borax in gold recovery.

**Awareness and Training Gaps among Miners:** Many artisanal miners are not aware of borax or do not have the technical training to use it correctly. Appropriate education and capacity building programs are needed to facilitate the safe and efficient use of borax (Appel & Na-Oy, 2012; 2014).

**Socio Cultural Resistance to Change:** Mercury's usage is a well-established part of traditional mining practices, and miners are resistant to adopting new methods if they feel that there were increased risks (Spiegel & Veiga, 2010).

**Geological Contexts Where Borax May Be Less Effective:** Borax does not work in all geological settings. For ores with high sulfide content or requiring higher melting temperatures, such as nickel ores, borax usage can be less effective and therefore requires a complementary process or more development (Appel & Na-Oy, 2012; Veiga, 2020).

**2.4 Previous Studies on Borax and Mercury**

Mercury has long been utilized in small gold mining due to its compatibility with gold particles.

Nevertheless, its impact on the environment and health prompted a search for safer alternatives such as borax.

Borax was first introduced in the Philippines and Tanzania, where it has been employed in small scale gold mining. In the Philippines, utilizing borax has proven to yield similar, and even increased gold recovery rates in comparison with mercury. Borax is easier to use in gold extraction allowing gold to be extracted easily from other minerals with a lower melting point (Appel & Na-Oy, 2012). In Tanzania, training programs on borax use for miners have also led to gradual adoption and a decrease in mercury exposure in mining communities (Veiga et al., 2014).

Research has demonstrated that borax gold recovery rates are similar to and in some cases slightly greater than what is experienced with mercury. For instance, the first borax method has been reported to recover 92–98% of gold in some cases matching or exceeding the efficiency of mercury retrieval (Veiga et al., 2014). These results are fundamental to follow on promoting borax as a safer and effective reagent for artisanal gold miners.

#### **2.4.1 Laboratory Experiments**

Controlled lab experiments inform us about how effective borax is and its impact on mercury and the environment.

##### **Effectiveness:**

Laboratory analyses have been shown that borax is an effective method for gold recovery, especially in combination with heat to form a borate glass that entraps gold particles. This technique not only achieves high recovery rates but also prevents the emission of toxic mercury vapors into the environment (Appel & Na-Oy, 2012; Appel and Jønsson 2010).

##### **Environmental Impacts**

Compared to mercury, comparative experimental studies have always shown the considerable environmental advantages of borax. On the other hand, while mercury, once emitted into the environment, contaminates air, water, and soil, whereas borax is a non-toxic substance, with minimum impact on the ecosystem (Appel & Na-Oy, 2012; Køster-Rasmussen et al., 2015). Controlled experiments have also demonstrated that borax-based methods produce no toxic

byproducts, so they are a sustainable option for artisanal miners.

#### **2.4.2 Socio-Economic Implications**

The socio-economic factors involved in substituting mercury with borax must be considered for its viability and acceptance in mining practice.

##### **Miners' Acceptance**

Miners have mixed feelings about substituting with borax. According to some studies, most miners readily transition to borax because it is less costly and easier to apply (Appel & Na-Oy, 2014). According to other studies, miners resist substituting with reluctance in not having information and training. For instance, Hilson & Pardie, 2006 mentioned that proper training programs and community dialogue matter in allowing miners to transition from utilizing mercury to utilizing borax.

##### **Cost Benefit Analyses**

From a financial consideration, substituting with borax is in its favor for Artisanal and small scale miners (ASGM) in terms of long term savings. Borax is less costly compared to mercury, and its use spares them medical expenses for mercury poisoning (Appel & Na-Oy, 2014). In addition, substituting with borax enables miners to obtain additional gold, and its use is therefore encouraged (Veiga et al., 2014).

#### **2.5 Limitations Identified in Existing Research**

Despite the positive results, existing literature on borax has some shortcomings that require to be addressed.

##### **Geological and Technical Constraints**

Borax will not always work under all types of geological settings. In some refractory gold zones or high sulfur ones, the effectiveness of borax-based methods can drop (Appel & Na-Oy, 2012; Veiga, 2020).

##### **Lack of Long-Term Studies**

Though the short-term environmental gains of borax are well established, long term research on

its ecological and social effects is lacking substantially. Most existing studies consider short term impacts, thereby leaving open questions regarding potential accumulation or unexpected effects.

## **2.6 Gaps in Current Knowledge**

While extensive studies have been performed regarding mercury and its alternatives in artisanal and small-scale gold mining (ASGM), significant gaps in information regarding geographical, socio-economic, environment, and policy aspects prevail, in particular. Bridging such gaps is critical in assuring efficiency and sustainability in borax use as a reliable alternative for gold extraction in gold mining operations.

### **2.6.1 Geographical and Contextual Gaps**

Regardless of positive results with regard to gold recovery using borax in specific regions, not enough studies have been conducted in regions such as in Ethiopia, with its specific geomorphologic and socio-economic settings.

Lack of Research in Ethiopia: Most studies of borax have focused in regions such as South America and Southeast Asia, with little study conducted in African countries such as in Ethiopia (Appel & Na-Oy, 2012). The geologic region of Benishangul Gumuz, with its specific ore types and socio-cultural settings, warrants localized studies to assess its suitability in its specific environment.

Diversity in Ore Types: Mineralogy and gold ore composition vary remarkably with geographical locations. Despite its success in gold recovery in specific ore types, little information regarding its effectiveness with specific geo-morphologic settings in Ethiopia, such as with its alluvial placer and quartz veins gold ore types, prevails.

### **2.6.2 Socio-Economic Factors**

The role of socio-economic factors in changing mining practice acceptance is critical. Nevertheless, most studies in the current literature have overlooked such factors:

Cultural and Socio-Economic Challenges: Traditional use of mercury in ASGM is widespread and deep-rooted in practice. Little study has been conducted with regard to cultural resistances in taking up borax, an important consideration in assuring success in intervention in Ethiopian gold

mining communities (Hilson & Pardie, 2006).

**Long-Term Economic Benefits:** While borax is considered cost-effective, there is insufficient research on its long-term economic advantages for miners, such as potential increases in productivity and income. A deeper understanding of these benefits could help promote borax adoption (Appel & Na-Oy, 2014).

### **2.6.3 Environmental Impacts of Borax**

Although borax is generally considered safer than mercury, its environmental implications require further study:

**Environmental Implications of Large-Scale Borax Use:** There is a lack of comprehensive studies on the long-term environmental impacts of widespread borax use, particularly its effects on soil and water ecosystems in mining regions (Türkbay et al., 2022).

**Comparative Studies on Long Term Impacts:** While mercury's toxicity and environmental harm are well documented, comparative research on the long-term ecological consequences of using borax versus mercury is limited, especially in the Ethiopian context (Veiga et al., 2014).

### **2.6.4 Policy and Regulation Gaps**

Policy frameworks are essential for facilitating the transition from mercury to safer alternatives, but existing policies are often inadequate:

**Insufficient Policy Frameworks:** Ethiopia lacks robust policies to regulate mercury usage and promote alternatives like borax. This regulatory gap hinders the implementation of mercury free practices in ASGM.

**Localized Strategies Aligned with Global Initiatives:** While the Minamata Convention aims to reduce mercury use globally, Ethiopia needs localized strategies tailored to its mining practices, socio-economic conditions, and environmental contexts to align with these global initiatives (UNEP, 2013).

## **Chapter 3**

### **Research Methodology**

#### **3.1 Study Area Description**

The study was conducted in the Assosa Zone of the Benishangul-Gumuz Region, Ethiopia, an area recognized for its significant gold deposits. The selected sites, Agosha Kebele and Mukufute Kebele, represent distinct mining contexts, quartz-vein-hosted primary ores and alluvial placer gold deposits, respectively. The geographic, geological, and socio-economic attributes of these sites underpin the evaluation of borax as an alternative to mercury in artisanal and small-scale gold mining (ASGM).

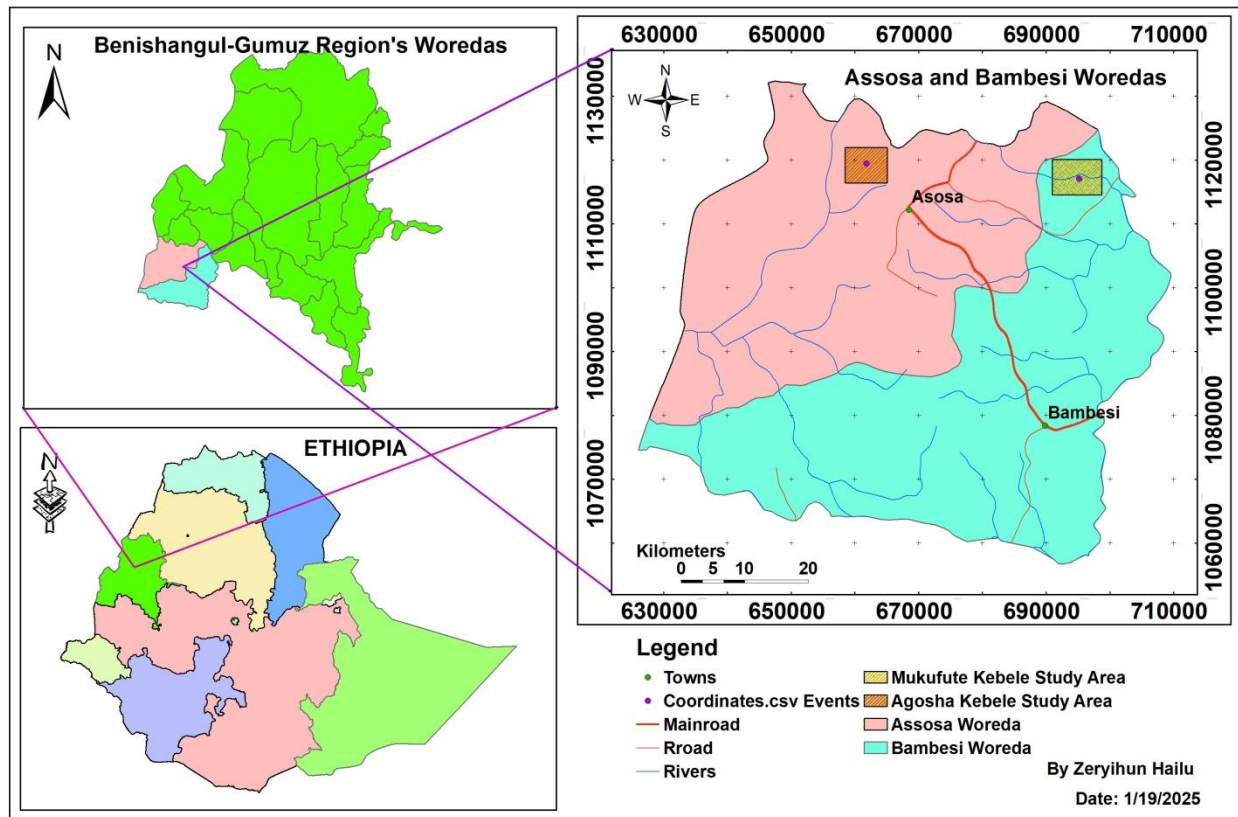
##### **3.1.1 Geographic Context**

The two study sites are Agosha Kebele and Mukufute Kebele, which are within reasonable access distances from Assosa, the administrative capital of Benishangul Gumuz Region (660 km Western of Addis Ababa). Agosha Kebele is located approximately 12 kilometers northwest of Assosa, and Mukufute Kebele is located about 30 kilometers to the northeast. The two sites can be accessed from Assosa, but the roads, especially during the rainy season, may require significant navigability and planning to reach, depending on the weather challenges.

Agosha Kebele (36P Zone, 0661770 E, 1119449 N; Elevation: 1,228 meters) stands out with its rough topography and significant rock outcrops, renowned for its dominant gold occurrences in its principal gold occurrences that are associated with quartz veins and hydrothermal environments, and therefore a key location for gold search and extraction operations. By contrast, Mukufute Kebele (Coordinates: 36P Zone, 0695143 E, 1117101 N; Elevation: 1,066 meters) encompasses comparatively low-lying terrain adjacent to perennial river systems, where primarily placer gold deposits generated via riverine mechanisms provide favorable high yield extraction opportunities along its riverbanks.

The general environment of the region in the zone of Assosa is characterized as being predominantly tropical with a wet period extending between June and September and a period of dry weather extending between October and May. Climate characterizes mining operations,

specifically placer mining, in its high dependency on water availability during wet times.



**Fig 3:1 Location Map of Study Area**

### 3.1.2 Geological Context

The Assosa Zone is part of the Ethiopian Precambrian basement complex and forms a significant part of the Neoproterozoic Arabian-Nubian Shield (NANS). There is an extensive record of metallogenic endowment, particularly of gold in the region (Bullock and Morgan, 2018).

#### Regional Geology

The geologic features of the Assosa Zone include high grade metamorphic lithologies, including garnet bearing gneisses, amphibolite schists, and migmatites, granulite facies metamorphosed during the Pan African orogen, between about 850 and 550 Ma. These geologic structures are invaded by syn to post tectonic granitoids (e.g., biotite granites and diorites) emplaced during the Neoproterozoic period of crustal stabilization (Temesgen Oljira et al., 2022; Natnael Wondera.

2017). Oblique collision of the cratons, with the respective East Saharan and East Arabian segments further contributing to shear zone and hydrothermal conduit formation that are essential for gold mineralization, describes the tectonic architecture of the Arabian–Nubian Shield (ANS) (Alam et al., 2021; Zhao et al., 2019; Wahed et al., (2021). Gold bearing quartz veins widespread in the region were formed during post collisional extension (~600–550 Ma), which occurred during a period of regional uplift and decompression melting according to geochronological studies dating the last magmatic activity to 636 Ma (Abebe Bedassa, 2014).

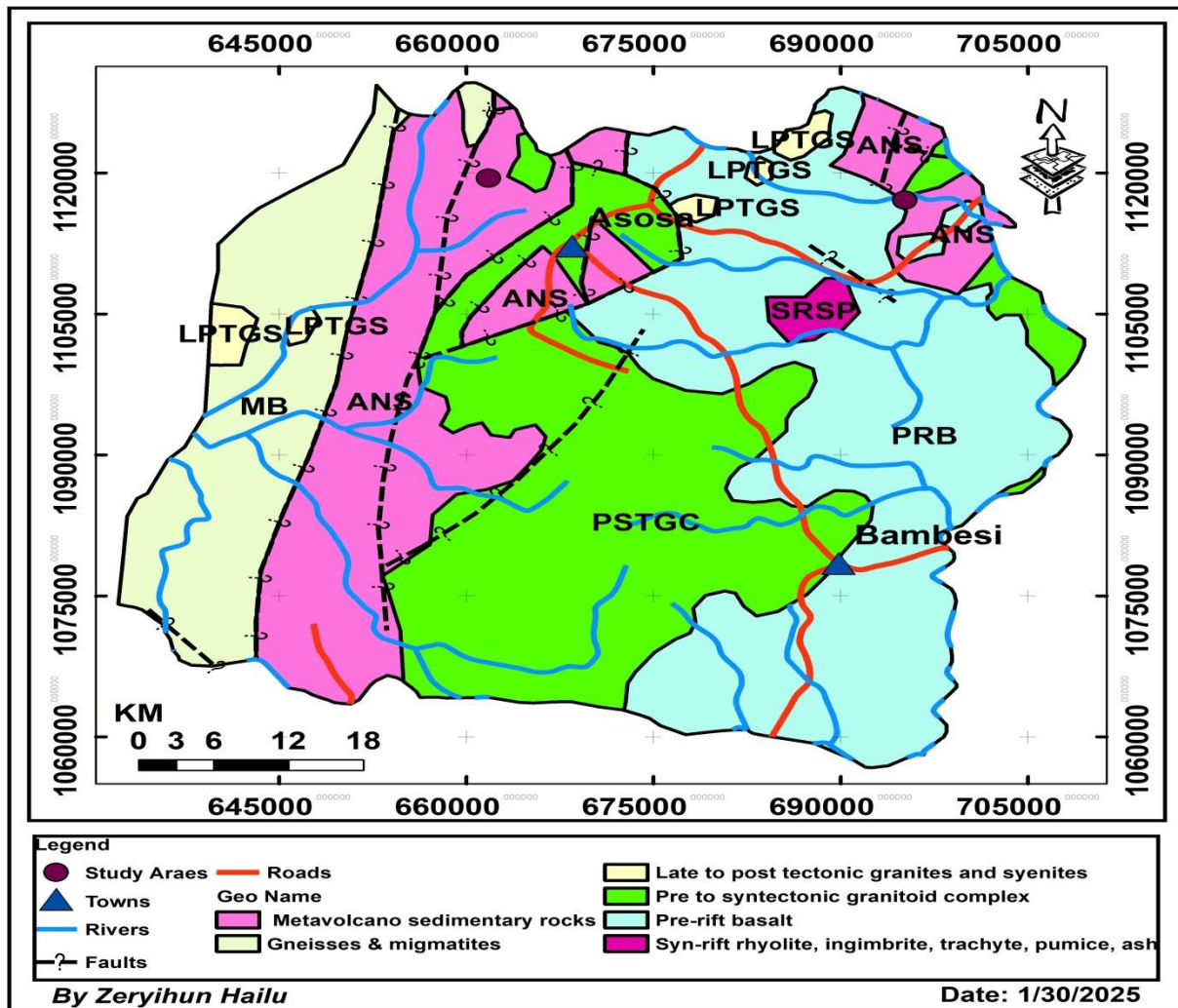


Fig 3:2 Local Geological Map

## **Local Geology**

Agosha Kebele: The quartz-vein-hosted primary ores gold mineralization is hosted in sulfide rich quartz veins that were emplaced in NNW–SSE trending shear zones. These show spatial association with biotite schists and garnetiferous gneisses and wherein gold forms microscopic inclusions in pyrite ( $\text{FeS}_2$ ) and arsenopyrite ( $\text{FeAsS}$ ). Alteration halos, predominantly characterized by sericitization and silicification, represent fluid rock reaction under temperatures between 250 and 350°C (Deksisa Debele and Koeberl Christian, 2004). Microprobe analysis reveals gold fineness values between 850 and 920, similar to values seen in orogenic type occurrences (Abebe Bedassa, 2014).

Mukufute Kebele: Most of the alluvial placer deposits are concentrated in alluvial terraces of Dabus River and they are derived from the erosion and weathering of quartz-vein-hosted primary ores sources in Agosha. Gold grains (0.5–2 mm) have rounded to sub rounded morphologies which indicate transportation in rivers for distances of 5–10 km. Quarterly averaged gold grades amount between 1.2– 1.8 g/t and Heavy mineral associated with the placers are dominated by magnetite, ilmenite, and zircon (Abebe Bedassa, 2014; Getnet Belachew, 2023).

### **3.1.3 Socio-Economic Context**

The inhabitants in the Assosa Zone rely predominantly on gold mining in a small and artisanal manner for survival, and in many cases, it forms a significant source of livelihood for many family heads, most prominently in rural areas with poor agricultural potentials (Netsanet Zeleke et al., 2024). Despite its widespread use for gold extraction, it comes with considerable health consequences and accelerates environment degradation, posing a danger both to miners and surrounding communities through its toxic releases of mercury and groundwater and aquatic life contaminations (Birhanu Bekele, 2022).

## **3.2 Research Design**

The current study utilizes field experimental research methods for testing the efficacy of borax as a substitute for mercury for gold extraction under small scale mining. The research conducted in Ethiopia's Benishangul Gumuz Region mimics actual field settings for maximum generalizability of the findings for the use of artisanal miners. In addition, this study readdresses major

shortcomings of the available research on sustainable mining practices with regard to comparing gold yield efficacy and cost savings of using borax against mercury processes (Appel & Na-Oy, 2014).

This study evaluates the efficiency of borax smelting compared to mercury amalgamation for small scale gold mining in Ethiopia, focusing on the Benishangul Gumuz Region, Asosa Area. Through controlled laboratory tests and statistical analysis, we assess whether borax smelting yields significantly higher gold recovery and whether ore type (Quartz-vein-hosted primary ores vs. Placer) affects recovery rates.

The study works with commonly available resources and machinery for setting up viable small-scale mining practices. Together, the empirical data and related studies provide a solid foundation for it to be considered in assessing the ultimate economic and environmental benefits of gold extraction using borax.

### **3.3 Sampling Techniques**

The sampling strategy has been carefully planned with the purpose of mimicking the heterogeneous conditions typical of Artisanal and Small-Scale Gold Mining (ASGM) in the study location. The major categories of samples acquired include quartz-vein-hosted primary ores and alluvial placer ones. The samples are proxies for the major mining sources analyzed in this specific study.

During the gold samples' process from quartz-vein-hosted primary ores, 60 kilograms of gold for every gold process technique conducted, i.e., for gold amalgamation and for gold smelting with borax, were achieved. The samples were from an actual working mining location, hence maintaining a variety of quality and composition typical of actual working environments.

In the study of alluvial placer deposits, 10 kg of samples were collected for testing of gold from riverbed and shallow workings. The samples were purposively chosen for testing the efficacy of borax against secondary gold deposits.

The employed technique of sampling conformed to established standards for purposes of reliability and representativeness. The preprocessing of the ore in its first step involved extensive washing with water, and then separation of the magnetic impurities with hand held magnets. The

preprocessing of this type served for purposes of achieving homogeneity of measurement in every experimental measurement.

### **3.4 Data Collection and Experimental Procedures**

The study performed an analysis of the efficiency of gold extraction linked to two common processing methods used in small-scale artisanal mining, namely mercury amalgamation and borax smelting. The independent variable tested was the ore type, where comparisons were drawn between alluvial placer sediments and quartz-vein-host primary ores; the dependent variable was the quantity of gold extracted, measured in grams. All experimental results were noted and statistically analyzed using Minitab 22.

The ore samples came from two different types of deposits: 60 kg of quartz vein ore with particle sizes less than 2 mm from Agosha Kebele, and 10 kg of stream sediment from Mukufute Kebele. Identical recovery methods for both sample types took place in a controlled laboratory environment that closely paralleled the conditions found in most small-scale mining operations.

The mercury amalgamation process is the careful mixing of mercury with finely powdered ore to form a gold-mercury amalgamates. Then the excess mercury is decanted and washed to separate gangue particles that may be left. The amalgamate is then heated at 450°C for 30 minutes in stainless steel containers to distill the mercury and produce crude gold.

In borax smelting, a homogeneous mixture of ground ore, sodium chloride, borax ( $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ), and water was prepared in a clay graphite crucible. Smelting was carried out in a charcoal-fired furnace at temperatures close to 950°C, with the admission of air to allow combustion. Gold particles, being denser, settled at the bottom of the crucible, while the lighter slag materials floated to the top. Controlled cooling to 200°C was carried out to allow the removal of slag and to further purify gold.

The additional materials and equipment used included Omo detergent for pre-washing the ore, locally sourced charcoal and firewood supplemented with oxygen to improve combustion, and freshwater from nearby creeks for ore washing and cooling. A 0.5 mm mesh size was used to allow separation of particle sizes. All the measurements of gold were taken using a precision scale having an accuracy of  $\pm 0.01$  g.

The effectiveness of the two methods was measured quantitatively by determining the gold recovery over each trial, thus providing a basis for the comparative efficiency of mercury amalgamation versus borax smelting under conditions applicable to field operations.

### **3.5 Data Analysis Techniques**

This study made use of both qualitative and quantitative approaches for measuring the efficacy and consequences of replacing mercury with borax for gold extraction in small scale gold mining in Ethiopia. The study made use of a controlled experimental setting for enabling gold recovery rates of both processes under equal experimental settings for determination. The data integrity was also guaranteed with statistical analysis with the use of the Minitab 22 software, involving descriptive and inferential statistical methods for determining data reliability. Visual presentations of trends, distributions, and variances of gold recovery rates between both processes were also created.

#### **3.5.1 Quantitative Analysis**

##### **Descriptive statistics:**

The performance parameters of the two techniques were quantified by determination of mean recovery rates, standard deviations, and minimum and maximum values and their ranges.

Graphical illustrations, including histograms and boxplots, were used for representation of distributions of the rates of recovery with regard to different key parameters.

##### **Inferential Statistical Analysis**

In order to compare the reliability and validity of research results, inferential statistical methods were employed for comparing gold recovery efficiency between gold extraction processes involving the use of borax smelting and those involving the use of mercury amalgamation. The statistical methods of choice were wisely matched with the data's properties, the experimental design, and the research goals, hence enabling a complete comparative examination of the gold extractions. The statistical comparisons were made under experimental conditions for testing if differences in the rates of recovery were significant and if there were variations in the performance of recovery when different ore samples were used.

A Wilcoxon Signed-Rank Test was conducted for testing paired gold values of recovery with regard to borax smelting and mercuric amalgamation. Since the data related to amalgamation had a non-normal distribution, a non-parametric hypothesis testing strategy was necessary. The testing process entailed assigning rank values for the paired differences with their signs intact, and then calculating the Wilcoxon test value (W). The significance of the measured difference against a pre-specified value of  $\alpha$  ( $\alpha = 0.05$ ) was compared for deciding if there existed a significant improvement in gold recovery with the use of borax smelting compared with mercuric amalgamation.

To explore possible variations in the rates of recovery of borax from quartz-vein-hosted primary ores and alluvial placer ores, a one-way Analysis of Variance (ANOVA) was conducted. Before performing the ANOVA, there were a variety of assumptions, such as the use of the Anderson-Darling normality and Levene's homogeneity of variances tests, thoroughly checked. If these assumptions were valid, ANOVA F-ratio and related significance tests would be calculated to assess if the mean differences between categories were significant. A correlation analysis was also conducted in order to find out if rates of recovery achieved from mercury amalgamation could be indicators of the efficacy of the process of borax smelting. This process of analysis involved generating scatter plots, calculating the Pearson's correlation coefficient if data had normality, or the Spearman's correlation coefficient ( $r$ ), and performing statistical tests for significance determination. The use of such inferential statistical techniques allowed derivation of scientifically valid, methodologically solid, and evidence driven conclusions from the research.

### **Visualization Tools**

In order to facilitate data interpretation and allow for comparative examination, different graphical presentations were made with the use of Minitab 22. The use of boxplots permitted testing for central tendency and variability with regard to gold recovery rates for mercury amalgamation and borax smelting, hence enabling identification of data dispersion and possible outliers. The generation of histograms permitted testing for trends in gold value distributions for values associated with every technique, hence identifying trends of skewness and variability. The use of scatter plots allowed for exploration of the relationship between the two methods'

recovery efficiencies, hence identifying trends of correlation. The use of interval plots also allowed for exploration of trends in variations of recovery rates for two categories of ore (alluvial placer and quartz-vein-hosted primary ores) in the process of borax smelting, hence contributing towards gaining a holistic understanding of performance variations under different geological settings. All these methods of presentation permitted systematic and understandable representation of statistical data.

### **3.5.2 Qualitative Analysis**

The qualitative study performed under this research provides a critical examination of the unquantifiable factors influencing the efficacy of gold recovery processes with the use of borax smelting and the use of mercury amalgamation. Environmental sustainability, human health consequences, usability in practice, and socio-economic factors, being qualitative, are critical factors towards defining the long-term sustainability of such methods.

### **3.6 Ethical Considerations**

#### **Informed consent and confidentiality.**

Participants were also supplied with complete information on research goals. Confidentiality was guaranteed with the anonymization of individual data and safe warehousing.

#### **Ecological Security**

The research conformed to regulations on the environment for limiting contamination.

- Mercury handling conformed to WHO safety requirements.
- Residual materials from experiments were disposed of per UNEP recommendations.
- Environmental monitoring has been conducted pre experiment and after the experimentation.

Through the use of rigorous ethical requirements and methodologies, this research ensures pragmatic, scalable, and environmentally sound solutions for gold mining in the ASGM industry.

## **Chapter 4**

### **Results and Discussion**

#### **4.1 Quantitative analysis of Gold Recovery Efficiency**

This chapter offers a complete review of the relative efficacy of gold extraction methods, i.e., mercury amalgamation and borax smelting, in the Benishangul Gumuz Region of Ethiopia. In addition, this chapter discusses statistical and experimental methods used for their efficacy, variability, and appropriateness for gold yield. Later sections take a quantitative approach with statistical techniques, including descriptive statistics, normality tests, and hypothesis testing for comparing the excellence of one process with the other. Apart from this, qualitative factors, i.e., working viability, environment, and socio-economy, are also discussed for giving a complete idea of the relative efficacy of such methods of extractions.

##### **4.1.1 Gold Recovery Rates: Amalgamation vs. Borax Smelting**

Table 4.1 depicts a comparative study of gold recovery methods, separating them into those with and without the use of amalgamation and borax smelting. The results of tests conducted show that, under perfect conditions, gold recovery levels were higher with the use of borax smelting compared to mercuric amalgamation. Precisely, under perfect conditions, the highest gold recovered from mercuric amalgamation was 1.04 g, compared to 1.12 g when utilizing the use of borax smelting. The values are from 20 comparative tests conducted for both methods.

**Table 4.1: Gold Recovery Rates (g) from Amalgamation and Borax Smelting**

Tests ID	Amalgamation (g)	Borax smelting (g)	Ore type
Test-1	0.1	0.5	Quartz-vein-hosted primary ores
Test-2	0.4	0.5	Quartz-vein-hosted primary ores
Test-3	0.23	0.61	Quartz-vein-hosted primary ores
Test-4	0.44	0.91	Quartz-vein-hosted primary ores
Test-5	0.34	0.8	Quartz-vein-hosted primary ores
Test-6	0.55	0.86	Quartz-vein-hosted primary ores
Test-7	0.07	0.18	Quartz-vein-hosted primary ores
Test-8	0.25	0.68	Quartz-vein-hosted primary ores
Test-9	0.18	0.75	Quartz-vein-hosted primary ores
Test-10	0.12	0.45	Quartz-vein-hosted primary ores
Test-11	0.13	0.22	Quartz-vein-hosted primary ores
Test-12	0.09	1.1	Alluvial Placer Deposit
Test-13	0.29	0.32	Alluvial Placer Deposit
Test-14	1.04	1.12	Alluvial Placer Deposit
Test-15	0.07	0.09	Alluvial Placer Deposit
Test-16	0.08	0.95	Alluvial Placer Deposit
Test-17	0.06	0.07	Alluvial Placer Deposit
Test-18	0.09	1.01	Alluvial Placer Deposit
Test-19	0.11	0.98	Alluvial Placer Deposit
Test-20	0.05	0.15	Alluvial Placer Deposit

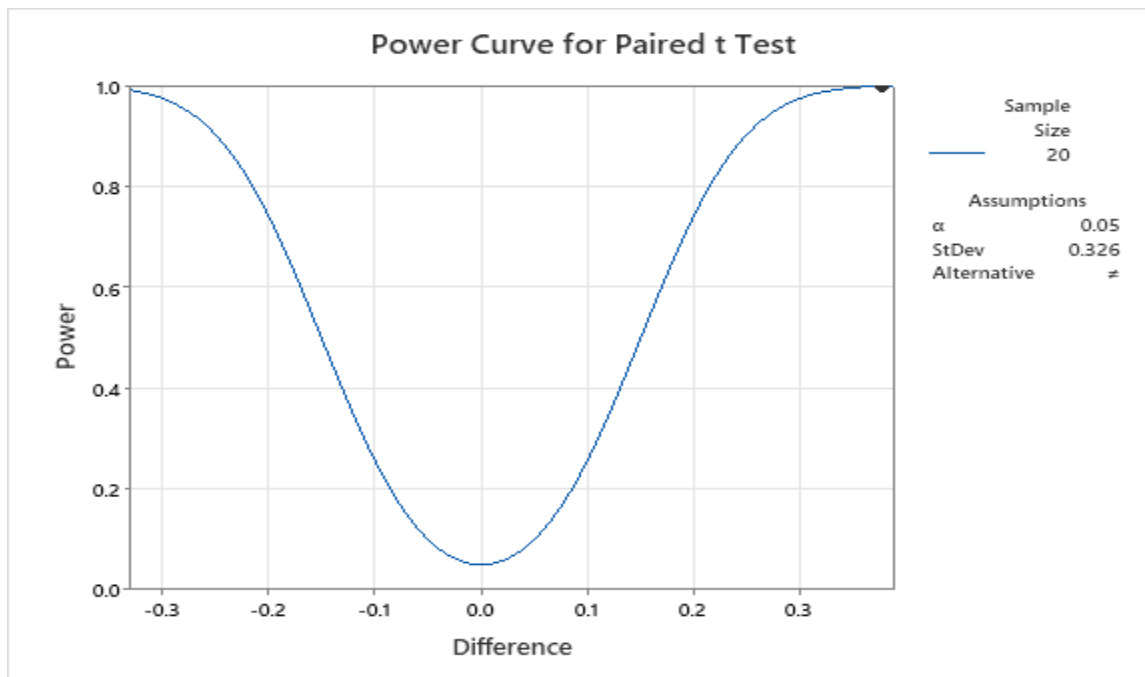
#### 4.2 Power Analysis and Statistical Reliability

Power analysis represents a critical statistical approach being employed for measuring the probability of identifying a defined effect size, on the hypothesis of there being a real effect, and of achieving enough statistical power for valid inference. In this study, a paired samples approach has been employed for enabling calculation of the power; testing hypotheses such as the Null Hypothesis ( $H_0$ ) stating the paired mean difference is 0, and the Alternative Hypothesis ( $H_1$ ) stating the paired mean difference not being 0. With  $\alpha = 0.05$  significance and under the hypothesis of the paired differences' standard deviation being 0.326, a calculation of the power

has been performed for a sample of 20 subjects. The output of this calculation of the power has been represented in the table format in Table 4.2 and has also been represented with a related graphical representation in Figure 4.1.

**Table 4.2: Power Analysis Results**

Mean Difference	Sample Size	Power
0.378	20	0.99841



**Figure 4.1: Power Analysis Output**

To ensure adequate statistical power, there needs to be more than the widely accepted 0.80. The statistical power of 0.99841, calculated for this study, indicates a very high statistical power, and this indicates a very solid statistical testing methodology. In addition, this result indicates a very low possibility of a Type II error, defined as failing to reject a false null hypothesis.

The substantial statistical power of this study provides significant guarantee of the reliability of research findings, enabling solid conclusions on gold recovery rates in terms of both the technique of mercury amalgamation and the technique of borax smelting. In addition, greater statistical power supports other statistical techniques, including hypothesis testing, normality

testing, and variance testing.

### 4.3 Statistical Analysis of Recovery Rates

#### Descriptive Statistics

Table 4.3 illustrates a complete table of descriptive statistics of the rates of recovery, including key statistics such as the mean, standard deviation, and minimum and maximum values for every technique being used.

**Table 4.3: Descriptive Statistics for Gold Recovery Methods**

Variable	N	Mean	SE Mean	StDev	Minimum	Median	Maximum	Range
Amalgamation (g)	20	0.2345	0.05325	0.23812	0.05	0.125	1.04	0.99
Borax smelting (g)	20	0.6125	0.07898	0.35319	0.07	0.645	1.12	1.05
Mean Difference	20	0.378	0.07295	0.32625	0.01	0.355	1.01	1

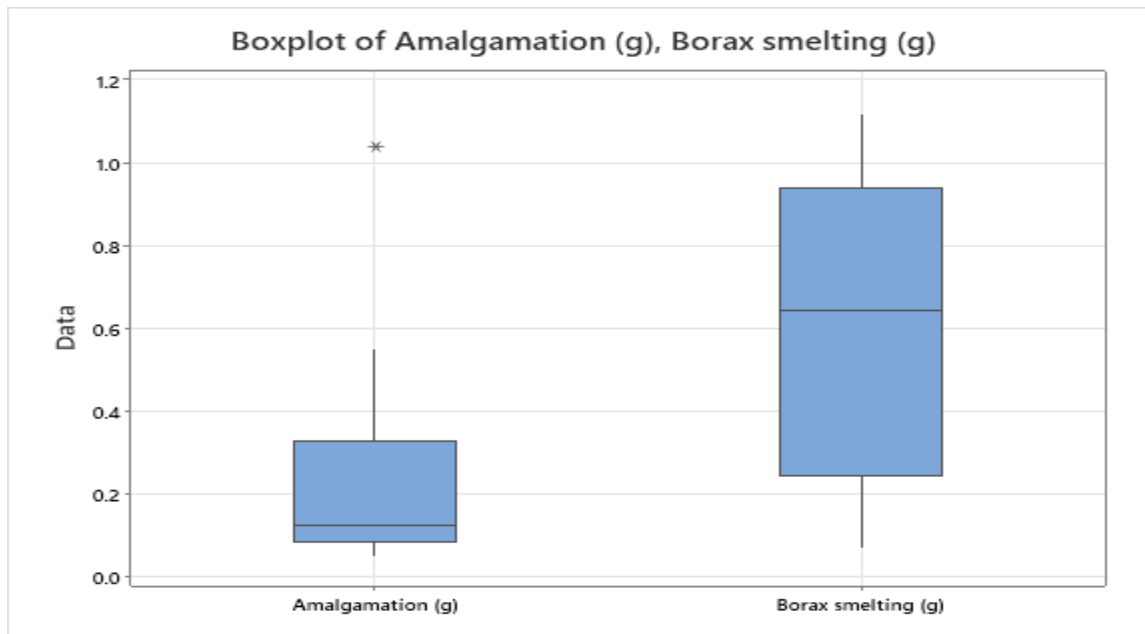
The average gold recovered with the use of borax smelting (0.6125 g) is considerably higher compared to what can be recovered with amalgamation (0.2345 g), hence highlighting the greater efficacy of borax in gold extraction. The standard deviation of 0.35319 g for borax smelting outweighs its value for amalgamation (0.23812 g), implying higher variability in the rate of recovery. The variability can be contributed to a variety of factors, such as the ore composition, quality of the ore, temperature of process, geological environment, and working conditions. The median of 0.645 g for borax smelting also supports its higher efficacy compared to 0.125 g for amalgamation. The mean of 0.378 g of difference points towards the significant higher efficacy of borax smelting.

The smelting process with borax enhances working efficacy by holding small gold particles that may be lost in the process of mercury amalgamation. In addition, it contributes towards generating purified gold by forming a glass like slag when being smelted, which skillfully encloses impurities (Appel & Na-Oy, 2012).

#### Boxplot Analysis

The examination of the boxplot (Figure 4.2) also supports a comparative study of different gold

recovery methods, including their median values, IQR, and identification of outlier values. The study's findings point towards a considerably higher median rate of gold recovery for borax smelting compared with amalgamation, hence highlighting its higher efficacy. The larger IQR of borax smelting indicates higher versatility towards different samples, even if also indicative of variations related to composition of the ore, process parameters, and levels of operator skills. The presence of top end outlier value, indicated by maximum value of 1.12 g, also supports the efficacy of achieving maximum gold recovery under optimal parameters of borax smelting. The narrower IQR and lack of top end outlier values for amalgamation, on the other hand, point lower rates of gold recovery and hence its lower efficacy for smaller gold grains.



**Figure 4.2: Boxplot of Gold Recovery Rates for Amalgamation and Borax Smelting**

#### 4.4 Normality Assessment

Statistical analyses also commonly require data normality testing for the determination of the appropriate testing methods. In the course of this research, the normality of data for gold extractable from amalgamation and smelted using borax were tested using the Anderson-Darling test. The use of this test is necessary for setting up the requirements under which hypothesis testing can be conducted with both parametric and non-parametric statistical methods, hence the

validity of ensuing tests performed.

The Anderson-Darling test has been utilized in order to check if the datasets of the processes of amalgamation and smelting of borax satisfy a normal distribution. The statistical technique tests the discrepancy of the empirical cumulative distribution function (ECDF) from the expected normal cumulative distribution function (CDF). The null hypothesis ( $H_0$ ) suggests data normality, and the alternative hypothesis ( $H_1$ ) suggests the presence of non-normal data. The value from the result of the Anderson-Darling test is then compared with a critical value (CV) of 0.692, for a significance level of 5% ( $\alpha = 0.05$ ), in order to conclude. The null hypothesis is not accepted (rejecting the hypothesis of normality) if the test statistic exceeded the critical value of 0.692. If, on the other hand, the test statistic of 0.692 and lower, then the null hypothesis still stands, and this indicates data satisfaction with a normal distribution. The result of this two-dataset data analysis is shown in Table 4.4.

**Table 4.4: Anderson-Darling Normality Test Results**

Dataset	Test Statistic (AD)	Critical Value (CV)	p-value	Decision
Amalgamation (g)	1.688	0.692	< 0.05	Not normally distributed
Borax Smelting (g)	0.431	0.692	> 0.05	Normally distributed

The results of the normality tests present a significant discrepancy between the two data sets: the data for amalgamation (AD = 1.688) has passed beyond the critical value (0.692), hence, signifies a lack of normal distribution, unlike for the data on borax smelting (AD = 0.431), which is still under this value and indicates normality. The discrepancy guides the choice of the optimal statistical approach for testing recovery efficiencies. Due to the fact that the data for amalgamation is not normally distributed, the classical test (paired t-test) cannot be employed in practice and a nonparametric alternative, the Wilcoxon Signed-Rank Test, is required. The Wilcoxon Signed-Rank Test becomes useful for comparing two related data sets when normality assumptions are violated, enabling a more precise determination of gold recovery efficiencies between gold processes of amalgamation and borax smelting.

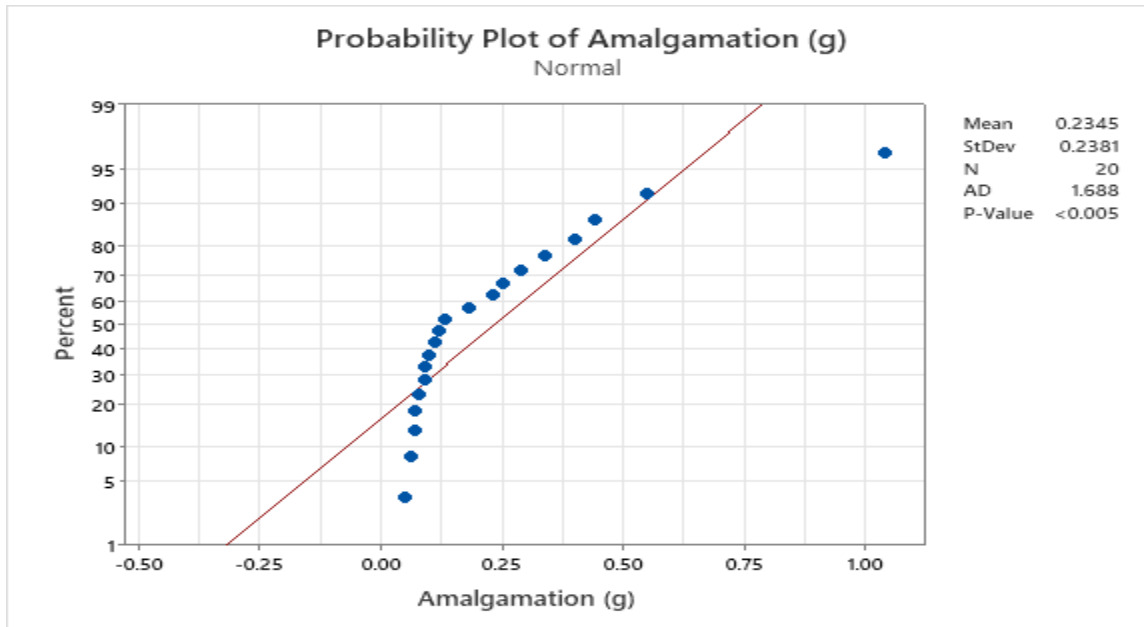


Figure 4.3: Probability plot of Amalgamation (g) recovery data.

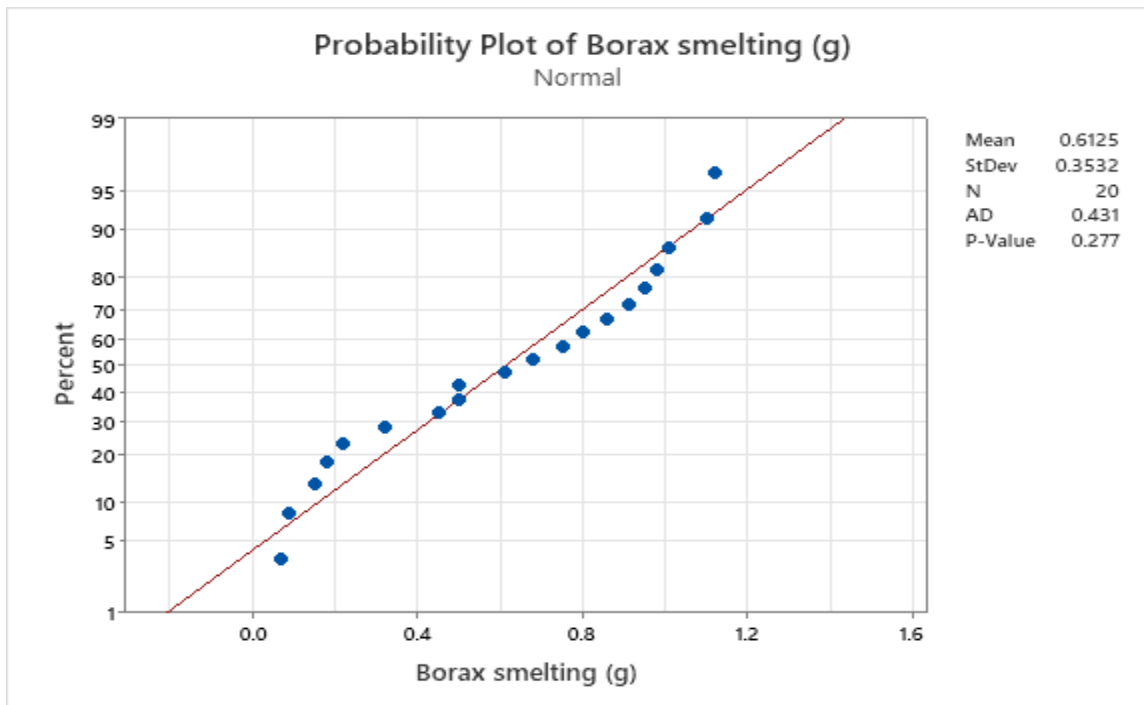


Figure 4.4: Probability plot of Borax Smelting (g) recovery data.

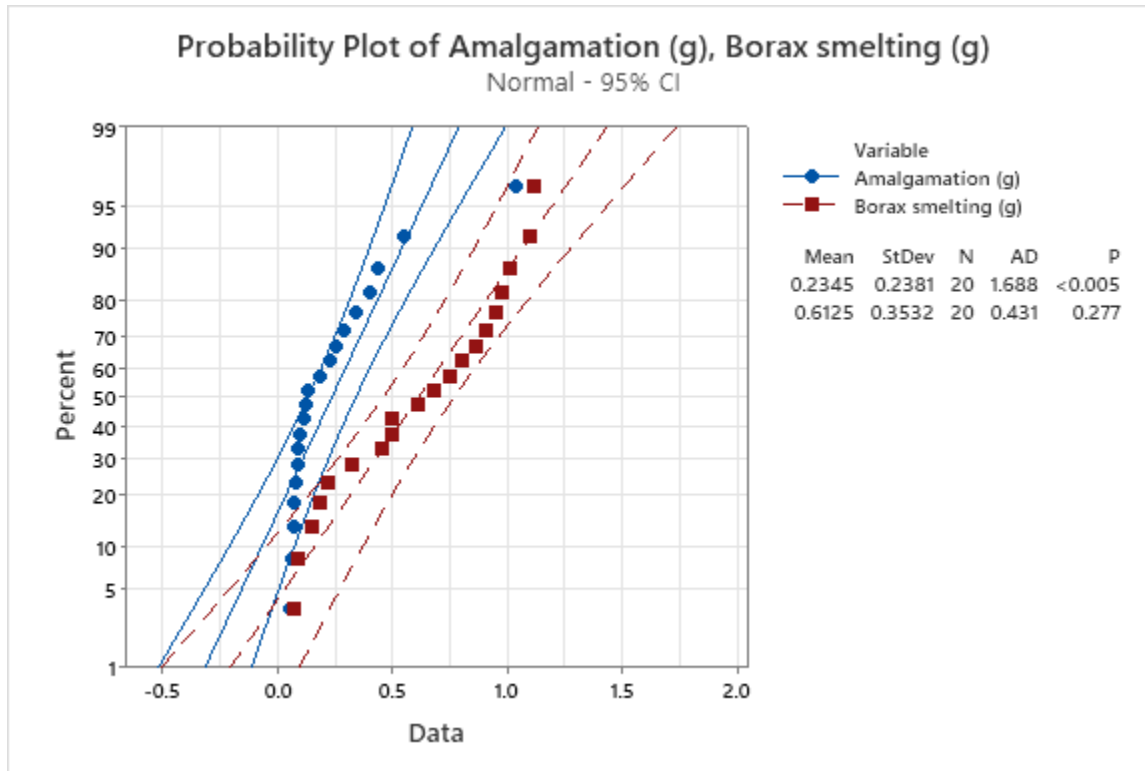


Figure 4.4: Combined probability plot of Amalgamation and Borax Smelting (g).

### Wilcoxon Signed-Rank Test

In order to assess the statistical significance of identified disparities, a Wilcoxon Signed-Rank Test was conducted, and its result can be seen in Table 4.5.

Table 4.5: Wilcoxon Signed-Rank Test Results

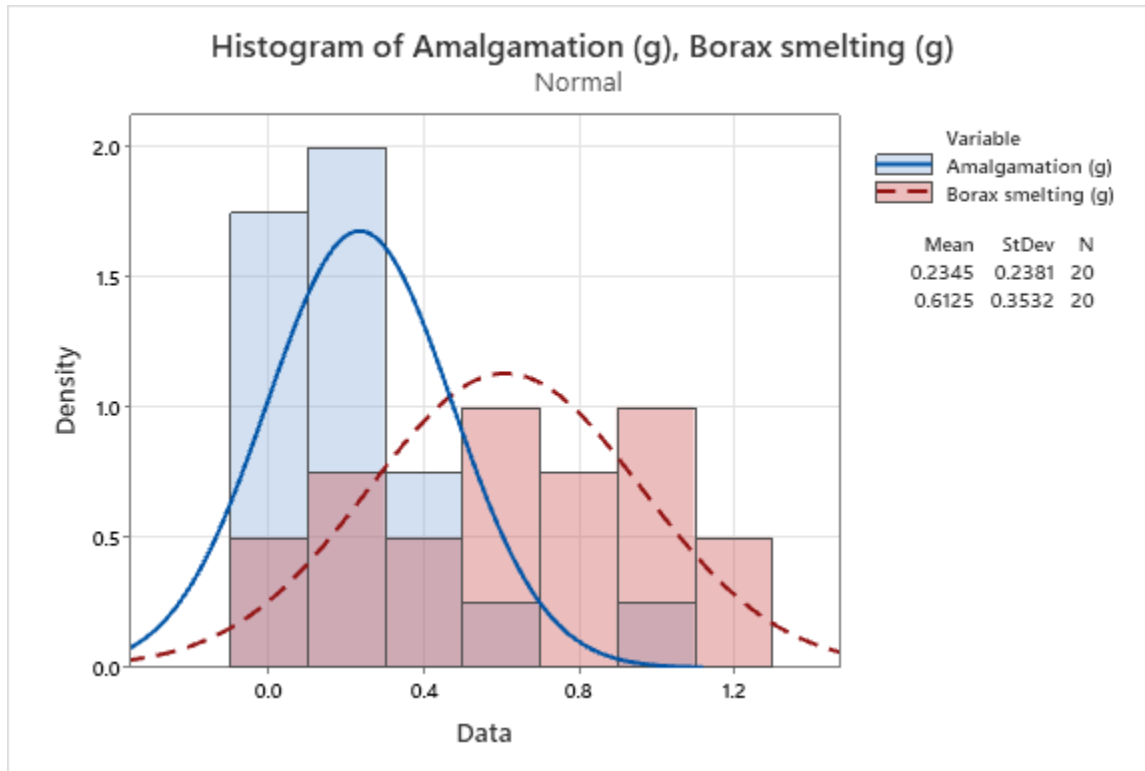
Null hypothesis		$H_0: \eta = 0$	
Alternative hypothesis		$H_1: \eta \neq 0$	
Sample	N for Test	Wilcoxon Statistic	P-Value
Mean Difference	20	210	0

The outcomes of the Wilcoxon Signed-Rank Test suggest a statistically significant difference in gold recovery between the use of mercury amalgamation and the use of borax smelting, with a p-value of 0.000, considerably lower compared to the 0.05 significance value. This finding supports the inference of varying recovery efficiencies of the two methods. Therefore, I reject the null hypothesis ( $H_0$ ) that there is no difference in the recovery of efficacy of the two methods.

The alternative hypothesis ( $H_1$ ) of there being a significantly higher gold recovery from the use of borax smelting compared to amalgamation, on the other hand, is confirmed. Statistically, this suggests there is not a zero disparity ( $\eta \neq 0$ ) between the paired values of gold recovery, hence reinforcing the observation of greater efficacy of the use of borax smelting for gold extractions. The findings also strengthen the case for the use of borax smelting being more effective and more environmental and human healthy compared to the use of techniques involving mercury. The significantly higher rate of recovery efficiency of gold with the use of borax smelting underscores its ability to increase gold recovery and mitigate the environment and human health related dangers of the use of mercury.

### **Histogram Analysis**

The examination of the histogram (Figure 4.6) indicates prominent distribution trends with regard to gold recovery rates for both processes of mercury amalgamation and borax smelting. The histogram for mercury amalgamation illustrates a skewed distribution with a heavy concentration of recovery rates with lower values, indicative of persistently low performance with low levels of variability. Though there are sporadic appearances of higher values, their rarity has minimal contribution towards overall performance. The histogram for borax smelting, on the other hand, illustrates a wider and more even distribution with more values and higher frequencies of higher values. This indicates higher flexibility and performance in the process of borax smelting, with its capacity for achieving average and higher levels of recovery rates, and higher mode of higher performance compared to amalgamation.

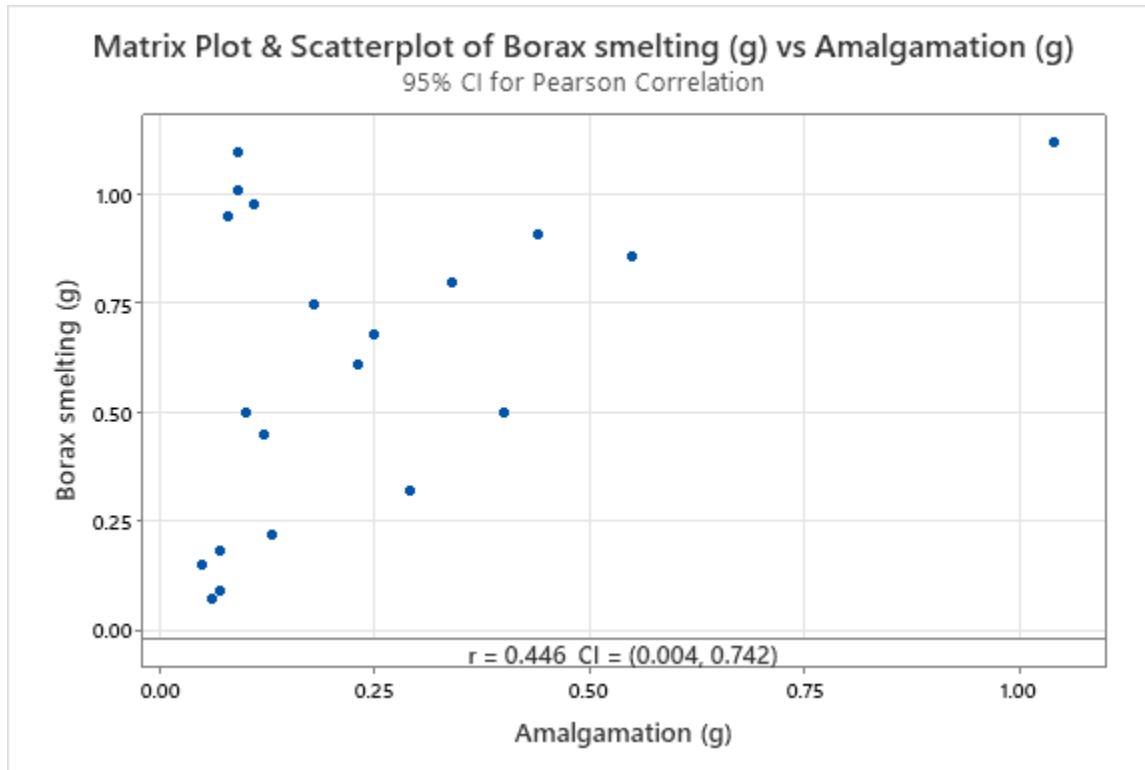


**Figure 4.6: Histogram of Gold Recovery Rates for Amalgamation and Borax Smelting**

**Scatter Plot Analysis:**

The analysis of Figure 4.7 indicates a weak to moderate correlation ( $r = 0.446$ ) between the recovery rates of borax smelting and amalgamation, suggesting that even though there exists a relationship, the performance of one process does not constitute a viable predictor for the other. The relationship between them is defined by inherent differences between the two processes: amalgamation relies on chemical reactions with mercury, and the requirements of gold being recovered with heat and flux. The scatter plot has a wide range of data points with no apparent linear relationship, highlighting the idea of the two processes being independent. Also, there are data points implying that there can be higher rates of recovery with borax smelting even where there are inferior rates of recovery with amalgamation, highlighting its possible efficacy irrespective of performance associated with gold recovered from mercury. The findings emphasize the need for Artisanal and Small-Scale Gold Miners (ASGM) to compare the performance of borax smelting independently when phasing down from mercury, and not

comparing against historical performance from amalgamation.



**Figure 4.7: Scatter Plot of Amalgamation vs. Borax Smelting Gold Recovery**

#### 4.5 Variance and Homogeneity Tests

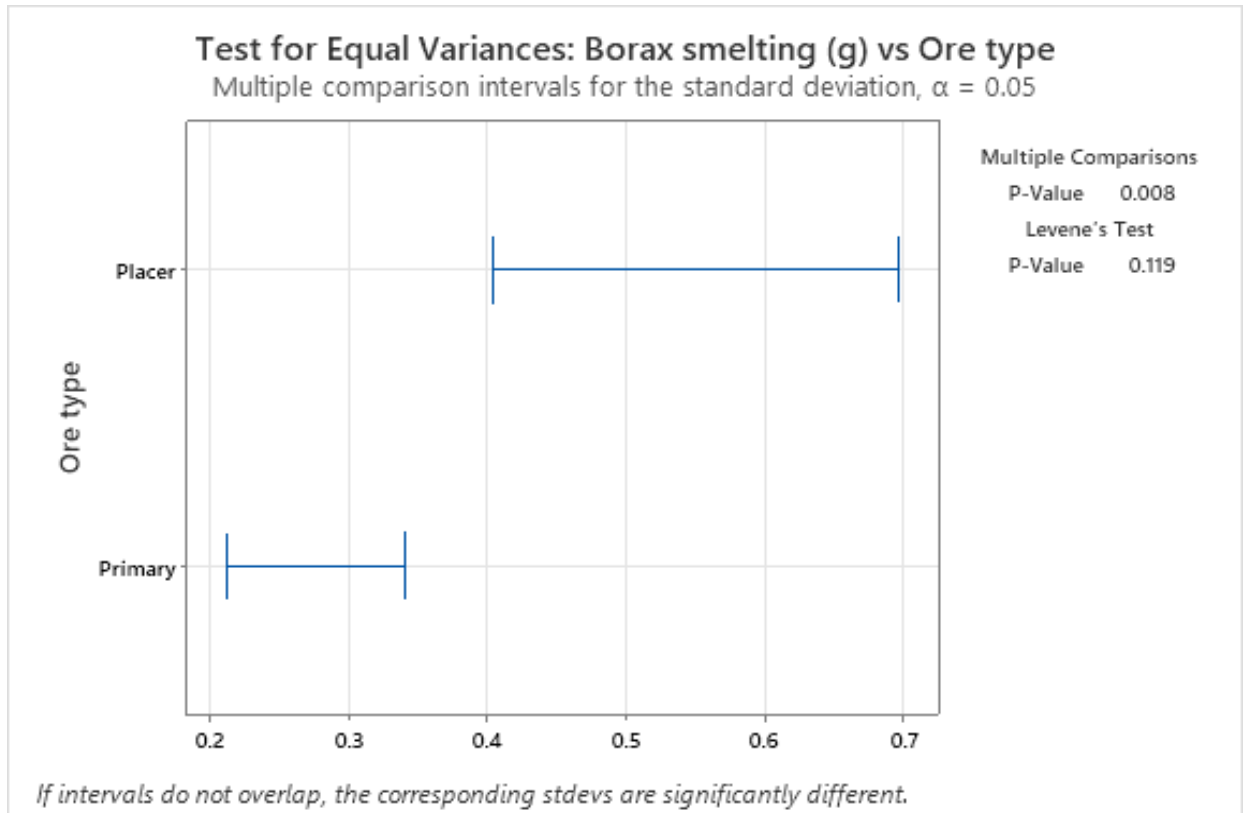
The Levene's Test has been conducted to determine if there was a significant statistical difference in gold recovery rates between different categories of quartz-vein-hosted primary ores and alluvial placer ore and their association with borax smelting. The test tests for homogeneity of variances, a necessary pre-requisite for performing parametric statistical tests, i.e., one-way ANOVA. The null hypothesis has been considered for equal variances, and alternative hypothesis for more than one differentiating variance. In this study, significance value ( $\alpha$ ) has been considered 0.05 for testing significance of variations of variances.

The results of Levene's Test, as shown in Table 4.7, are 2.68, with its associated p-value of 0.119, greater than the significance value of 0.05. The result points towards there not being enough evidence for the rejection of the null hypothesis, hence implying there are not significant differences in the variances of gold recovery rates from quartz-vein-hosted primary ores and

alluvial placer ore from the process of borax smelting. The homogeneity of variances, therefore, can be said to be satisfactorily assumed. While the standard deviation of quartz-vein-hosted primary ores ore (0.469) and alluvial placer ore (0.244) is different, these differences are deemed less important as compared with Levene's test. With data being normal and equal in their variances, there then exists a need for the use of a parametric approach, with the use of one-way ANOVA being the applicable technique for testing the significance of the differences in the rates of borax smelting for quartz-vein-hosted primary ores and alluvial placer ore.

**Table 4.6: Levene's Test for Equal Variances**

Null hypothesis		All variances are equal	
Alternative hypothesis		At least one variance is different	
Significance level		$\alpha = 0.05$	
Ore type	N	StDev	CI
Placer	9	0.469095	(0.353836, 0.828143)
Quartz-vein-hosted primary ores	11	0.243766	(0.157075, 0.475114)
Individual confidence level = 97.5%			
Method		Test	P-Value
Levene		2.68	0.119



**Fig 4.8: Test for equal variances**

#### 4.5.1 One Way ANOVA by Ore Type

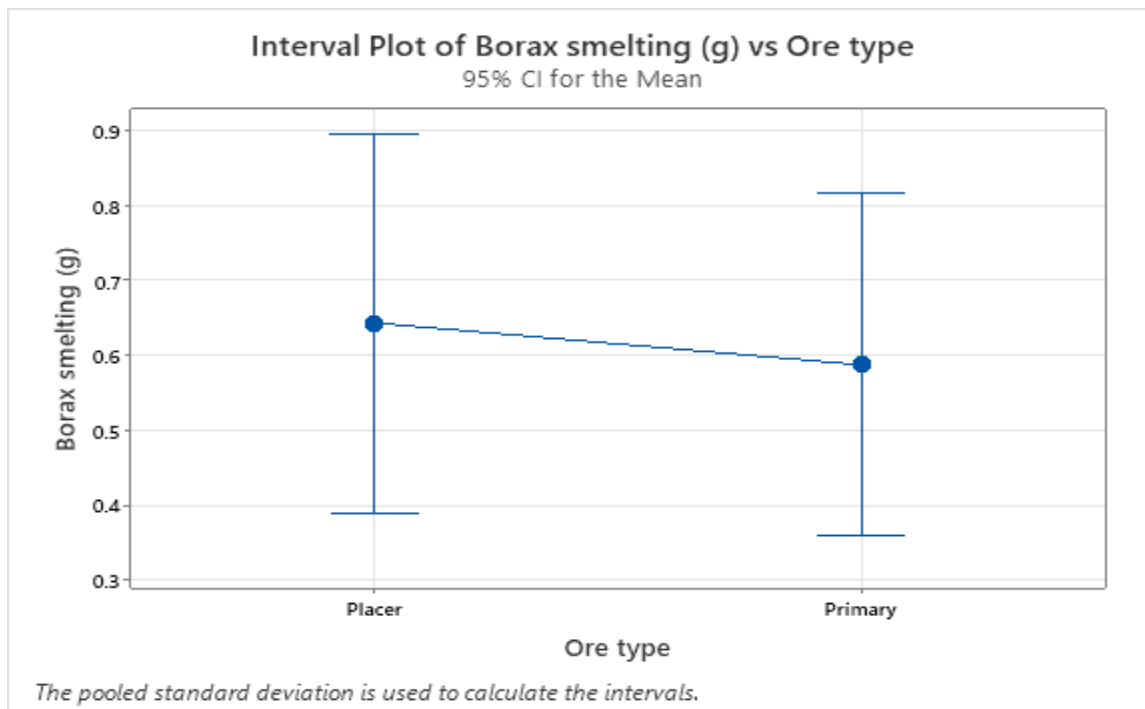
A one-way ANOVA was performed in order to ascertain if gold recovery via borax smelting exhibits significant variations between quartz-vein-hosted primary ores and alluvial placer ore categories. The purpose of this research was to find out if there exist variations in average gold recovery rates between these geological categories. Table Figure 4.7 indicates from the ANOVA result, the F-value was 0.12 and the associated p-value of 0.734, which considerably surpasses the 0.05 significance value.

These findings show no statistically significant variation in smelting effectiveness using borax applied on quartz-vein-hosted primary ores versus alluvial placer ores. This conclusion is also asserted through the interval plot shown in Figure 4.9, which demonstrates superimposed confidence intervals for the two ore categories. Therefore, this indicates that gold recovery through borax-facilitated smelting is constant regardless of ore type utilized. The result indicates geological variations don't affect the efficacy of the use of borax smelting, making it a solid and

viable process for gold recovery in artisanal and small-scale gold mining (ASGM) processes. The efficacy of other gold recovery processes, on the other hand, may be impaired by the mineralogical constitution of the ore, hence reducing their viability as a global alternative for mercury use in different ore environments.

**Table 4.7: ANOVA Results for Borax Smelting Recovery Rates by Ore Type**

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Ore type	1	0.01556	0.01556	0.12	0.734
Error	18	2.35462	0.13081		
Total	19	2.37017			



**Fig 4.9: Interval Borax smelting (g) vs ore type**

#### 4.6 Qualitative Analysis

### Environmental Implications of Gold Recovery Methods: Mercury Amalgamation vs. Borax Smelting

The concept of sustainability of the environment has been a major point of study in the context

of artisanal and small-scale gold mining (ASGM) because of its reliance on methods of gold extraction involving heavy use of mercury. The use of mercury amalgamation has been widely documented as primary source of pollution, causing significant degradation of soils, contamination of water, and atmospheric discharges posing long term threats to ecological systems and human populations (Appel & Na-Oy, 2014). Conversely, the use of borax smelting has been identified as being more environmentally friendly, with the capacity for mercury elimination and, at the same time, optimal levels of gold recovery performance (Appel & Na-Oy, 2014). Even without primary ores and secondary environment data, this study, relying on research and theories, provides significant understanding of the relative ecological impacts of these two processes.

### **Ecological Risks of Mercury Amalgamation**

The phenomenon of mercury pollution stands among the greatest of the environment related problems associated with artisanal and small scale gold mining (ASGM). Evidence illustrates that only 10–30% of the mercury consumed in the process of amalgamation ends up combining with gold, with the remaining amount being emitted into the environment through tailings, wastewater, and atmospheric emissions (Veiga et al., 2014). In mined regions, mercury residues settle on terrestrial and aquatic environments, where microbes reduce them into very toxic methylmercury. This type of mercury then becomes bioaccumulated in aquatic environments, causing contamination of fish populations and posing significant human health threats for people relying on such water sources for their water needs and for their use in fishery (Gibb & O’Leary, 2014).

Another major issue is the release of mercury during incineration of gold amalgams, which is vaporized upon incineration and released into the atmosphere contributing to pollution at regional scales and with varying distances of transport and global deposition, thus aggravating the mercury contamination at the global scale (Telmer & Veiga, 2009). The remaining mercury in mining tailings reduces agricultural soils' productivity, leaving such soils infertile for years. The persistence of mercury in the environment and its adverse effects on human health (i.e. neurological, renal and reproductive effects) have led to worldwide engagement, such at the Minamata Convention on Mercury, to restrict its usage in artisanal and small-scale gold mining

(ASGM) ([Hindersah et al., 2018](#); [WHO, 2024](#); [UNEP, 2013](#); [US EPA, 2022](#)).

### **The Environmental Benefits of Borax Smelting**

In position with the mercury amalgamation process, there exists a different technique called borax smelting, where there is a closed system, hence elimination of harmful pollution from being discharged into the environment ([Appel & Na-Oy, 2014](#)). The naturally forming mineral called borax acts as a flux, reducing gold's melting point and enabling its removal from other impurities. The process has been identified with zero mercury release and harmful by products, hence being considerably less harmful for miners and surrounding ecosystems ([Veiga et al., 2014](#)).

Moreover, the process of smelting borax does not depend on water usage, hence reducing the possibility of heavy metal contamination of adjacent rivers and groundwater. Also, the waste produced from the process of smelting borax leads to a glass like slag, and this immobilizes the impurities, hence not releasing them into the environment ([Appel & Na-Oy, 2014](#)). This also adds to the sustainability of the use of borax in reducing the footprint of artisanal and small-scale gold mining (ASGM) on the environment.

### **Policy and Sustainability Considerations**

Ethiopia, akin to other many countries with thriving Artisanal and Small-Scale Gold Mining (ASGM) industries, faces a growing need for developing regulations for reducing the environmental impacts of small-scale gold mining. The Minamata Convention on Mercury, ratified by Ethiopia, supports a transition towards gold mining practices without the use of mercury, hence upholding global sustainability goals ([Telmer & Veiga, 2009](#); [UNEP, 2013](#)). The use of borax smelting in Ethiopian ASGM practices can facilitate the country's performance of its environmental requirements and also promote miners' safety and health.

From an economic perspective, shifting to borax smelting could reduce long term environmental remediation costs associated with mercury pollution. Contaminated soil and water require extensive rehabilitation efforts, which can strain both local and national resources. Additionally, miners using borax smelting avoid exposure to toxic mercury vapors, reducing medical costs and improving overall community wellbeing ([Appel & Na-Oy, 2014](#); [Telmer & Veiga, 2009](#); [U.S.](#)

EPA, 2022; Jiang et al., 2024)

#### **4.7 Discussion**

The comparative gold recovery efficiency with the use of borax smelting and mercury amalgamation, analyzed in this research, offers valuable lessons on their efficacy, reliability, and ecological impacts. The findings suggest gold recovery rates via borax smelting are higher compared with gold recovered via mercury amalgamation. Descriptive statistical inference supports the observation of a greater mean gold recovery of 0.6125 g via borax smelting compared with a mean gold recovery of 0.2345 g via mercury amalgamation. This difference, confirmed with the Wilcoxon Signed-Rank Test ( $p\text{-value} = 0.000$ ), supports the observation of higher performance with borax smelting. In addition, statistical analysis of the data with a boxplot also depicts higher gold recovery and indicates a wider interquartile range (IQR) for gold recovered with the use of borax smelting, highlighting its flexibility under different conditions. The occurrence of extreme outlier values of gold recovered with the use of borax smelting adds even more validity of its possible efficacy under optimal smelter environments. The narrower IQR of gold recovered with the use of mercury amalgamation, on the other hand, suggests lower gold recovery with lower variability, highlighting its limitation in gold recovery from smaller gold particles.

The assessment of normality via the Anderson-Darling Test supports the statistical significance of the results. Though the dataset for borax smelting complies with normal distribution ( $AD = 0.431, p > 0.05$ ), the dataset for amalgamation does not ( $AD = 1.688, p < 0.05$ ). Therefore, the use of non-parametric statistical tests, including the Wilcoxon Signed-Rank Test for paired comparisons, proved inevitable. The result of such tests, indicated via a Wilcoxon Statistic of 210 and significance of 0.000, offers significant statistical evidence for the efficacy of borax smelting compared to mercury amalgamation. The results indicated on the scatter plot ( $r = 0.446$ ) also imply a weak relationship between the two methods, with the gold recovery rate of one process not being able to reliably predict the other's efficacy. The discovery indicates the two methods rely on different underpinnings one being the affinity of gold for mercury because of their bond forms, and the other relying on heat for gold removal from its matrices.

The examination of homogeneity of variances, indicated by Levene's Test ( $p = 0.119$ ), supports the hypothesis of gold recovery rates for quartz-vein-hosted primary ores and alluvial placer ores being statistically indistinguishable, hence fulfilling the requirements for ensuing parametric tests. Consequently, a one-way ANOVA ( $F = 0.12$ ,  $p = 0.734$ ) was performed to determine if there are significant differences in the associated recovery rates for borax smelting between quartz-vein-hosted primary ores and alluvial placer ore categories. The lack of significance of the related  $p$ -value indicates there is no effect of ore type on the efficacy of borax smelting, hence implying equal performance under different geological settings. The result of the interval plot also supports this inference, with overlapping intervals of quartz-vein-hosted primary ores and alluvial placer ores implying there are not significant differences in the rates of recovery. The observation has significant implications for artisanal and small-scale gold mining (ASGM) practices, highlighting the flexibility and reliability of the process of borax smelting under varying ore composition.

In addition to statistical efficiency, the environmental impacts of mercury amalgamation compared to those of borax smelting present a major reason for the use of mercury free methods of extraction. The problem of pollution of the environment with mercury from artisanal and small scale gold mining (ASGM) is a major global environment problem, causing chronic impacts on soil degradation, water pollution, and air pollution. On the other hand, borax smelting eliminates the use of mercury, reduces harmful discharges, and minimizes contamination dangers. Through glass slag generation when the process of smelting occurs, borax skillfully encloses the impurities, hence inhibiting their liberation into the environment. These advantages align with Ethiopia's commitments under the Minamata Convention, whose purpose is the phasing out of the use of mercury in ASGM and the improvement of gold extraction practices towards sustainability. The research findings solidly support the use of borax smelting compared to mercury amalgamation, not only with higher rates of recovery, but also with lower environment and human dangers.

## Chapter 5

### Conclusion and Recommendations

#### 5.1 Conclusion

This research performs a critical examination of borax smelting as a substitute for mercury amalgamation for artisanal and small-scale gold mining (ASGM) in the Benishangul Gumuz Region of Ethiopia. The study finds that gold recovery with borax smelting is more effective, environment friendly, and more efficient compared with mercury amalgamation. The gold recovery rates were significantly improved when utilizing borax smelting, achieving a mean of 0.6125 g compared with 0.2345 g for mercury amalgamation. The Wilcoxon Signed Rank Test ( $p = 0.000$ ) supports the fact that this difference exists and is significant, hence highlighting the excellence of borax smelting in gold extraction.

Normality of the borax smelting dataset and amalgamation dataset were tested by Anderson–Darling Test, which showed borax was normally distributed, while amalgamation dataset failed to meet the condition. This result, therefore, made the use of non-parametric tests necessary for statistical validity. The data from Levene's test for homogeneity of variance ( $p = 0.119$ ) and one-way ANOVA ( $p = 0.734$ ) indicated variations in the recovery rates of borax smelting are not significant between different ore types (quartz-vein-hosted primary ores vs. alluvial placer deposit) and hence its versatility towards a variety of geological environments. The findings emphasize the dependability and reliability of borax smelting towards different mining environments, hence its viability compared to mercury-based processes.

Beyond gold recovery efficiency, the study underscores the environmental and health benefits of borax smelting. Mercury use in ASGM contributes to severe soil, water, and air pollution, leading to long term health risks such as neurological disorders and respiratory diseases. The Minamata Convention on Mercury aims to phase out mercury use in mining, and this study's findings strongly support the adoption of borax smelting as a practical, mercury free alternative that aligns with Ethiopia's environmental commitments.

Overall, this study confirms that borax smelting is not only a technically and economically feasible alternative to mercury amalgamation but also a more sustainable solution for ASGM in

Ethiopia. The method offers higher gold recovery rates, reduces environmental contamination, and minimizes health risks, making it a superior choice for small scale miners. However, successful implementation of borax smelting requires coordinated efforts from policymakers, researchers, and mining communities. By promoting mercury free gold recovery, Ethiopia can enhance ASGM productivity, protect public health, and achieve its environmental commitments, thereby contributing to a more sustainable and responsible mining sector.

## **5.2 Recommendations**

Based on the findings of this study, a number of recommendations are proposed to facilitate the shift from mercury amalgamation to borax smelting in artisanal and small-scale gold mining (ASGM) activities. Awareness raising programs and training programs need to be introduced with the objective of informing miners about the advantages of borax smelting, particularly highlighting its greater efficiency in gold recovery and environmental sustainability. In addition, the establishment of demonstration projects in main mining zones has been proposed for the purposes of gaining practical experience in gold recovery techniques using borax. All this is expected to instill confidence among miners in borax smelting and facilitate its extensive use in ASGM communities.

In terms of policy and regulation, the government of Ethiopia ought to tighten controls on mercury application in ASGM, as per the Minamata Convention on Mercury. Legal frameworks need to be reinforced for limiting imports of mercury and use will eliminate this harmful practice. Additionally, assistance in finance and logistics must be offered to miners undertaking shifts to mercury free gold recovery processes. The development partners and government agencies must make access to resources easily available so that borax smelting can be implemented without a cost for miners.

To ensure a seamless and sustainable transition, technical and economic assistance must be offered to ASGM communities. This involves subsidized access to borax and improved smelting equipment, reducing the financial burden on miners. Second, collaboration among government agencies, NGOs, and mining cooperatives is also crucial in offering miners' equipment, technical expertise, as well as market access. All these will make borax-based processing a viable and

long-term substitute for mercury amalgamation.

Further research and data gathering are required for scientific information on borax smelting and its usage in Ethiopia's ASGM industry. Field research has to be investigated in order to establish long term economic benefits of smelting borax, such as how it can lead to livelihood improvement among the miners and environmental cost savings on rehabilitation. There should also be research into geological conditions that have reduced effectiveness in borax smelting, as well as alternative gold extraction techniques appropriate for diverse ore types. Enhancing knowledge of borax smelting use will lead to its increased application and best practice.

For long term sustainability, borax smelting must be integrated into the National ASGM Action Plan of Ethiopia so that mercury free gold recovery is promoted as part of sustainable mining in the country. Incentives for mercury free gold processing must be introduced to encourage miners to drop mercury. These can be in the form of monetary compensation, tax breaks, or subsidies to buy borax and smelting facilities. Bringing Ethiopia's domestic mining legislations into international environmental compliance will serve to chart the country into responsible and sustainable gold mining activities.

To ensure correct usage of borax smelting in ASGM, training and capacity development programs must be developed encompassing policymakers, universities, and NGOs. These programs must cover imparting the technical expertise for mercury free gold recovery and stressing the environmental, health, and economic benefits of borax smelting. Building structured training programs will enable the sharing of best practices, facilitate the adoption of borax based processing, and enhance the long term sustainability of ASGM in Ethiopia.

In order to close existing knowledge gaps and further enhance the sustainability of borax use in ASGM, future research should cover the following topics:

Geological Contexts – Carry out detailed studies that aim to determine the feasibility of building a borax smelter in various geological settings and Ore types in Ethiopia.

Cumulative Effects on Public Health and Environments – Discuss the total environmental effects associated with borax smelting, including its long-term viability. Further, analyze the health outcomes of mercury-free extraction processes and their usefulness to miners and neighboring

communities.

Socio-Economic Dynamics – Discuss the socio-cultural determinants of miners' readiness to embrace borax smelting techniques and formulate effective strategies to counter resistance and myths about mercury free gold mining technologies.

Policy Effectiveness Evaluation – Evaluate the efficacy of policies aimed at minimizing the use of mercury and encouraging the use of borax and areas where the execution of such policies requires improvement.

Technological Innovation/development- Investigating complementary technologies that can enhance the extraction of gold obtained from borax-based processes in complex ore setting, improving efficiency and scalability.

Through the adoption of these recommendations and research priorities, Ethiopia can successfully transition to sustainable, mercury free gold mining, delivering economic gains to ASGM communities while meeting national and international environmental commitments.

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