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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

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Abstract: Artisanal and small-scale gold mining (ASGM) is important to the Ethiopian economy, especially in the Benishangul Gumuz Region. But ASGM also uses mercury extensively during gold recovery, raising public and environmental health concerns. This study assesses the feasibility of using borax as an alternative to mercury for gold extraction. Comparisons focused on a series of ore samples collected from quartz-vein-hosted primary ore and placer gold deposits in the Assosa area. Wilcoxon Signed-Rank tests, ANOVA, and descriptive statistics were employed to collectively analyze gold recoveries by methodologies, borax smelting and mercury amalgamation. Results showed that borax smelting significantly improved gold yield, with a mean recovery of 0.6125 g compared to 0.2345 g with mercury. The results also found borax was technically, economically, and safely viable. This study recommends adoption of this method within ASGM in Ethiopia and suggests further funding for the study of borax, including further recommendations for mandated policies and further research into the future long-term environmental impacts of borax and its scalability.

Keywords: *Borax Smelting; Mercury-Free Gold Recovery; Artisanal and Small-Scale Gold Mining; Environmental Sustainability; Benishangul Gumuz; Ethiopia.*

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I. INTRODUCTION

Artisanal and small-scale gold mining (ASGM) is an important economic activity for many developing countries, providing subsistence income for millions of people, especially in rural and under-resourced areas. In Ethiopia, Benishangul Gumuz Region is one of the most active locations for ASGM; gold mining is a key livelihood because of poor agricultural productivity, limited formal employment options, as well as negative social and cultural stigma around the practice (Teku, 2025; Zeleke et al., 2024, 2024; Tariku, 2021). In spite of its socioeconomic importance, the sector remains unregulated, ruled by informal practices that lack environmental safeguards, and use mercury in the recovery process (Hilson & Pardie, 2006).

Mercury is commonly used in ASGM through amalgamation, chemically combining with gold ore to form an amalgam that, once combined, is heated to cause the mercury to evaporate into the environment. This method is simple and effective in fine gold recovery but has the unintended consequences of releasing mercury to air, soil and water, which introduces long-term risks to ecosystems and significant health risks for miners and surrounding municipalities (Driscoll et al., 2013; Gibb & O'Leary, 2014). Environmental introduction occurs persistently, especially in aquatic systems where methylmercury accumulates and biomagnifies through the food chain (Driscoll et al., 2013). Research from Ethiopia has shown that mercury caused pollution of water sources and soils for agriculture in ASGM regions could further exacerbate local vulnerability for ASGM communities (Gelaye, 2022; Bekele, 2022).

In response to the international crisis posed by mercury, the Minamata Convention on Mercury an international treaty signed in 2013 calls for the reduction and, where feasible, the elimination of mercury use in the ASGM sector and by providing relevant options for alternatives (UNEP, 2013). Ethiopia is an adopter of this convention and is in the process of implementing the provisions outlined in the agreement although challenges lie ahead, most prominently that no

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feasible alternatives to mercury exist that are context relevant to Ethiopia (UNEP, 2013; Kabeta et al., 2024).

Of the very few alternatives examined in the world of ASGM, borax (sodium borate) was determined to be a viable replacement. Borax has been successfully employed in ASGM in the Philippines and Tanzania and is frequently used as a fluxing agent to lower the melting point of gold-bearing materials and smelt gold with non-harmful, non-toxic emissions (Appel & Na-Oy, 2012; Spiegel et al., 2018).

Borax is non-toxic, environmentally friendly, and readily accessible in many places, as opposed to mercury. Borax works by allowing gold particles to separate from impurities and sink to the bottom of the crucible during smelting at high temperatures, preventing the formation of chemically bonded by-products seen with mercury amalgamation (Appel & Na-Oy, 2012; Veiga et al., 2014). Despite its potential, the application of borax in Ethiopian ASGM remains limited and underexplored. There is a noticeable absence of empirical data on its effectiveness within the country's unique geological and socio-economic contexts. Ore types such as quartz-vein-hosted primary ores and alluvial placer deposits, which are prevalent in the Benishangul Gumuz Region, may respond differently to borax due to variations in mineral composition, sulfide content, and gangue material. Research indicates that factor such as high sulfide concentrations, pyrite and arsenopyrite, and the presence of clay and silicates can influence the efficiency of gold recovery during smelting (Appel & Na-Oy, 2012, 2014; Spiegel & Veiga, 2010). To address these gaps, the present study aims to evaluate the effectiveness of borax as an alternative to mercury in artisanal gold recovery under Ethiopian conditions.

II. OVERVIEW OF THE STUDY AREA

➢ *Location*

The research was conducted in the Assosa Zone of the Benishangul Gumuz Region, a geologically and economically significant area, located approximately 660 kilometers west of Addis Ababa, Ethiopia. Two active artisanal mining sites were selected as study area, Agosha and Mukufute, because they have differences in gold ore characteristics. The Agosha mining site is located roughly 12 kilometers northwest of Assosa city and is characterized by rugged terrain and hard-rock mining operations, while Mukufute mining site is located roughly 30 kilometers northeast of the Assosa city and is defined by lower-lying terrain with active placer mining along alluvial river terraces. Both are accessed by gravel roads although seasonal rains may also make access difficult and are a concern, especially during peak rainy season.

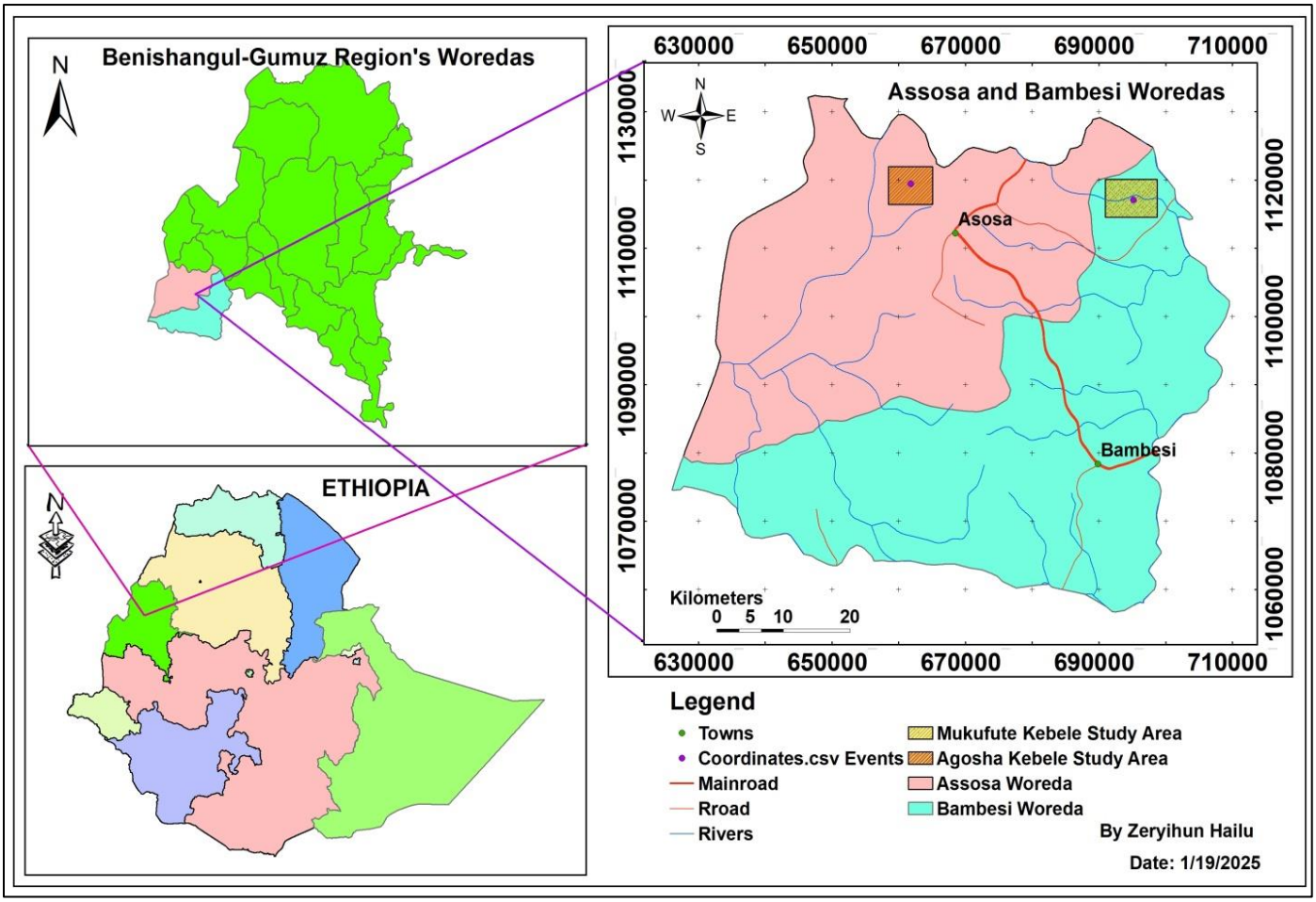

Fig 1 Geographical Location of Agosha and Mukufute Local Administrative Units Within Assosa Zone, Benishangul Gumuz Region, Western Ethiopia.

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➢ *Geology*

Geologically, the Assosa Zone represents the Arabian-Nubian Shield (ANS) that formed in the Neoproterozoic, containing a wide variety of metamorphic and igneous rock units that contain economically important gold mineralization. The most important lithologies are high-grade metamorphic rocks which include amphibolite schists, garnetiferous gneisses and migmatites metamorphosed during the Pan African orogen between about 850 and 550 Ma. These geologic structures are intruded by syn to post tectonic granitoids, such as biotite granites and diorites emplaced during the Neoproterozoic period of crustal stabilization (Zhao et al., 2019; Abu-Alam, Abd El Monsef, and Grosch, 2018; Wahed et al., 2021; Oljira et al., 2022; Wondera. 2017).

The geological development of the region and the oblique collision of the East Saharan and East Arabian cratons played an important role in producing regional NE-SW and NW-SE trending shear zones and hydrothermal conduit formation that are essential for gold mineralization (Oljira et al., 2022; Abu-Alam, Abd El Monsef, and Grosch, 2018; Zhao et al., 2019; Wahed et al., 2021). The gold mineralization occurred during the post-collisional extension period (~600-550 Ma). The geological evidence of this activity suggests that it involved the regional uplift and gravitational unloading induced by decompression melting, quartz-veins emplacement, in the case of the host rock type, and alteration halos containing demonstrable hydrothermal characteristics (Bedassa, 2014).

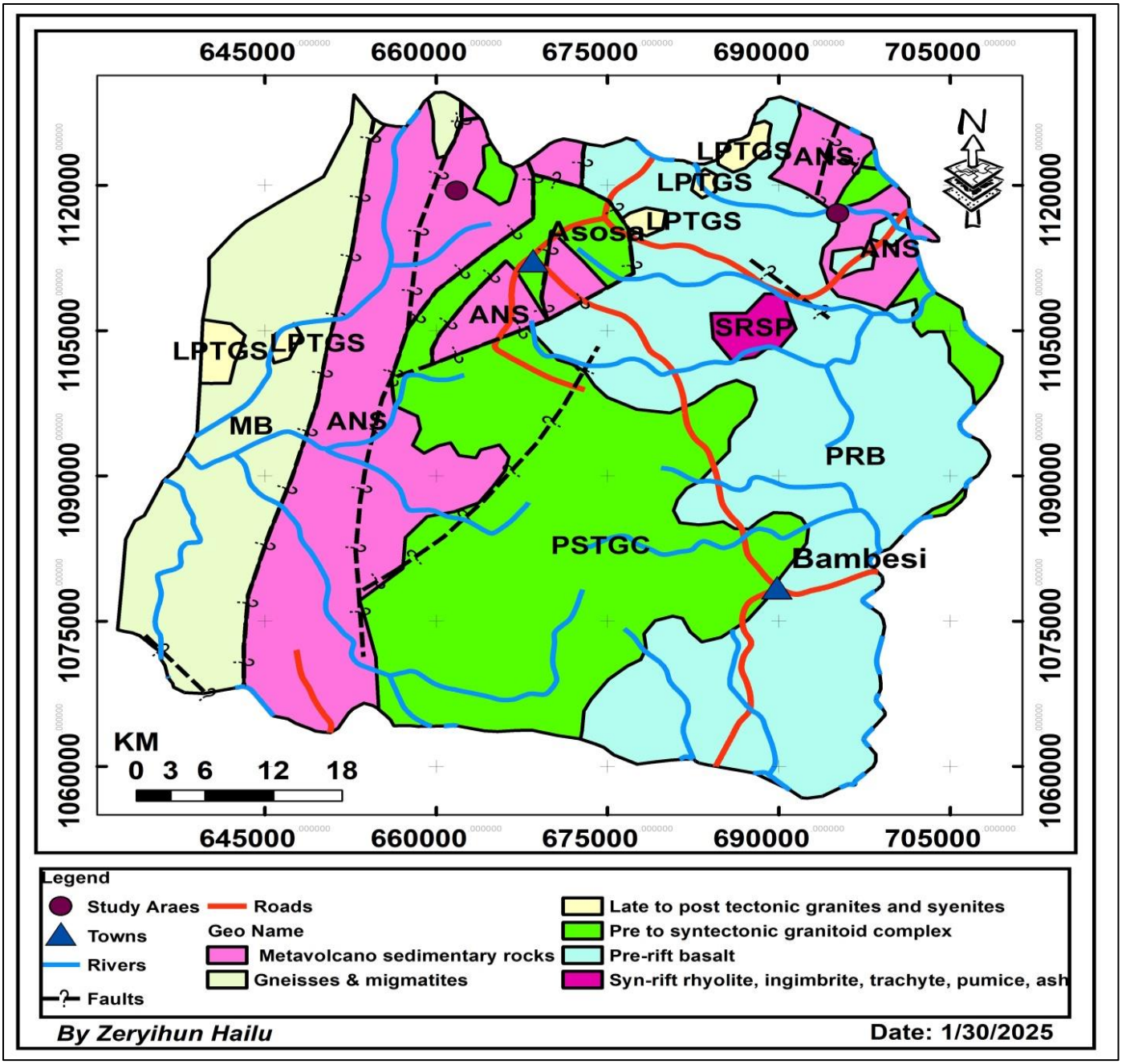

Fig 2 Local Geological Map Illustrating Quartz-Vein-Hosted Mineralization in Agosha and Placer Deposits in Mukufute Local Administrative Unit.

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Agosh's geology includes quartz-vein-hosted primary gold ores, which are spatially adjacent to biotite schists and garnetiferous gneisses. Gold mineralization is found in sulfide-rich quartz veins with pyrite (FeS_2) and arsenopyrite (FeAsS) lying on or spatially controlled by NW-SE trending shear zones. Gold was identified as microscopic gold inclusions in pyrite and arsenopyrite commonly noted with microprobe analysis. The altered host rock exhibited suspected hydrothermal alteration characteristics such as sericitization and silicification, likely indicating moderate to high temperature hydrothermal systems (250-350° C) (Debele and Koeberl, 2004). Microprobe analysis reveals fineness values of the gold found in this area ranged from 850 - 920, which is a typical value for orogenic gold deposits (Bedassa, 2014).

Mukufute is a geological site associated with alluvial placer gold scenarios mainly sourced from the erosion of evolved upstream quartz-vein-hosted deposits. The occurrence of placer gold is in fluvial sediments deposited along the Dabus River and tributaries. Gold grains generally range from between 0.5 mm and 2 mm and are rounded to sub-rounded form indicating a fluvial transport distance of 5–10 km. The heavy minerals accompanying the placer gold include magnetite, ilmenite, and zircon and the average gold grades are between 1.2 and 1.8 g/t (Belachew, 2023; Bedassa, 2014).

III. MATERIALS AND METHODS

➢ *Research Design*

This study employed a comparative experimental design under semi-controlled field conditions to evaluate the technical performance of borax smelting relative to mercury amalgamation in artisanal gold recovery. The central objective was to assess gold yield efficiency, variation across ore types, and the environmental safety of each method. Field experiments were carried out using locally sourced ore samples from both Agosha and Mukufute, representing quartz-vein-hosted primary gold ores and alluvial placer gold deposits respectively. These two methods were implemented using artisanal-scale tools and heating mechanisms to reflect the operational reality of Ethiopian ASGM practices.

Each extraction method, borax smelting and mercury amalgamation, was applied under standardized conditions to both ore types. This allowed for a direct performance comparison in terms of gold yield and operational feasibility. The study design was informed by best practices from similar evaluations conducted in other developing country contexts, such as the Philippines and Tanzania, where borax has been introduced as a safer alternative to mercury in artisanal gold mining (Appel & Na-Oy, 2012, 2014).

➢ *Sampling Techniques*

For the experimental trials, 60 kg of milled quartz-vein primary ore was randomly collected for each trial from active artisanal mines with the intention of capturing the inherent variability in both ore quality and geological characteristics. The samples were treated through a standard pretreatment process, entailing thorough washing with clean water to eliminate impurities such as clay, silt, and organic matter and followed by the removal of magnetic and paramagnetic particles with hand-held magnets. This process led to the reduction of the bulk material to a gold-enriched concentrate, which was then split evenly for processing using both mercury amalgamation and borax smelting methods. This process was carried out for eleven paired trials with the aim of determining the gold recovery efficiency of the two methods under real artisanal conditions.

At the same time, 10 kg of alluvial placer material was also sampled per trial from riverbeds and shallow artisanal pits, typical of the water-transported small gold particles that make up such deposits. Similar to the quartz-vein primary ore samples, the material from each trial was subjected to the same pretreatment protocol to enhance uniformity and remove impurities for further processing. The cleaned material then yielded a smaller concentrated portion, which was then split and processed into two equal parts using the mercury and borax methods, respectively. Nine paired trials were carried out in this study to compare the effectiveness of the two methods in extracting small-grained gold from placer deposits.

➢ *Experimental Procedure*

The methods were applied to equal quantity and type of ores to permit paired comparisons within trials. Twenty experimental trials for each method were conducted, with eleven trials for quartz vein ore type and nine for placer deposits, for a total of twenty paired observations.

- *Mercury Amalgamation*

In the mercury amalgamation procedure, concentrated ore samples were placed in metal basins and mixed with elemental mercury. This facilitated the formation of a gold-mercury amalgam, which was then filtered using cloth to remove gangue particles. The amalgam was placed in a stainless-steel container and heated to high emperature using a charcoal-fired oven. During this process, mercury vaporized and was released into the atmosphere, leaving behind a crude gold button. This method closely follows practices commonly employed by artisanal miners in the region and reflects the real exposure conditions faced by local communities.

- *Borax Smelting*

For the borax smelting method, the same quantity of pre-treated or concentrated ore was mixed with a combination of sodium borate ($Na_2B_4O_7•10H_2O$), sodium chloride, and water. The mixture was placed in a clay graphite crucible and subjected to smelting in a charcoal-fired furnace at higher temperatures. Air was supplied through manually operated bellows to enhance combustion. As the mixture reached melting temperature, the borax acted as a flux, lowering the melting point and forming a glassy slag that trapped impurities while the heavier gold particles settled at the bottom of the crucible. After cooling, the slag was removed, and the remaining gold was extracted. This procedure did not produce any toxic emissions and could be safely conducted using traditional artisanal tools.

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Finally, the recovered gold from both methods was measured using a digital precision balance with an accuracy of ±0.01 grams, ensuring reliable and reproducible results.

➢ *Data Analysis Techniques*

Quantitative data collected from the experimental trials were analyzed using Minitab 22 statistical software. For both methods of recovery and ore type descriptive statistics, mean, median, standard deviation and range were calculated to evaluate the central tendencies and variability.

The Anderson-Darling test was utilized to assess if the datasets were normally distributed. For paired comparison of the gold recovery results for the two methods, the Wilcoxon Signed-Rank Test was used at a 95% confidence interval ($\alpha = 0.05$). The Wilcoxon Signed-Rank Test was necessary in this case as it does not rely on the assumption of normality and is appropriate for paired observations. A one-way analysis of variance (ANOVA) was also completed to test if borax smelting performance differed across ore type. Prior to conducting the ANOVA, Levene's Test was used to test for homogeneity of variance. Spearman's rank correlation coefficient was also calculated to assess the relationship between the two methods when the same ore samples were tested. Visualizations, including boxplots and histograms produced as a part of the overall statistical output assisted with a deeper interpretation of the statistical findings and to identify possible trends and/or outliers and distributions.

IV. RESULTS AND DISCUSSION

➢ *The Comparison of Gold Recovery Efficiency*

The experimental trials of gold recovery that were carried out using mercury amalgamation and borax smelting noted a significant statistical and practical difference in gold recovery efficiency. Specifically, the results of twenty paired tests, comparing gold recovery efficiency for both ore types, demonstrated that borax smelting produced gold recovery values comprised of greater efficiency as opposed to traditional mercury amalgamation.

Across both ore types, the mean value of gold recovered using borax smelting was 0.6125 grams and the mean value using mercury amalgamation was 0.2345 grams.

During the trial, borax demonstrated clearly superior performance in all trials where it outperformed mercury amalgamation regardless of the type of ore being tested. While it is expected that borax would increase overall recovery rates for gold, the results also suggest that borax would also consistently produce results under different geological conditions.

Table1 Descriptive statistics of Gold Recovery (in Grams) Using Mercury Amalgamation and Borax Smelting

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 results generally endorse previous findings from other developing nations like Philippines and Tanzania that had suggested, borax has equivalent or better recovery efficiencies compared to mercury (Appel & Na-Oy, 2012; Veiga et al., 2014). Borax's recovery system has proven to be the strong fluxing capacity which assists with the separation of gold from silicate gangue.

➢ *Statistical Analysis of Recovery Performance*

In order to assess the significance of the observed differences in gold recovery performance between the two methods, an inferential statistical analysis was conducted. The Anderson-Darling normality tests indicated the data from mercury amalgamation did not come from a normal distribution ($p < 0.05$), while the data from borax smelting appeared to be normally-distributed ($p > 0.05$), as displayed in Figures 3. Since some of the data was not normally-forming, the Wilcox.on Signed-Rank Test was appropriate to assess the null hypothesis, which states there is no significant difference between the two gold recovery methods. Non-parametric tests are particularly useful for pairing datasets, and importantly, they allow tests, like the Wilcoxon, that do not assume any data distribution.

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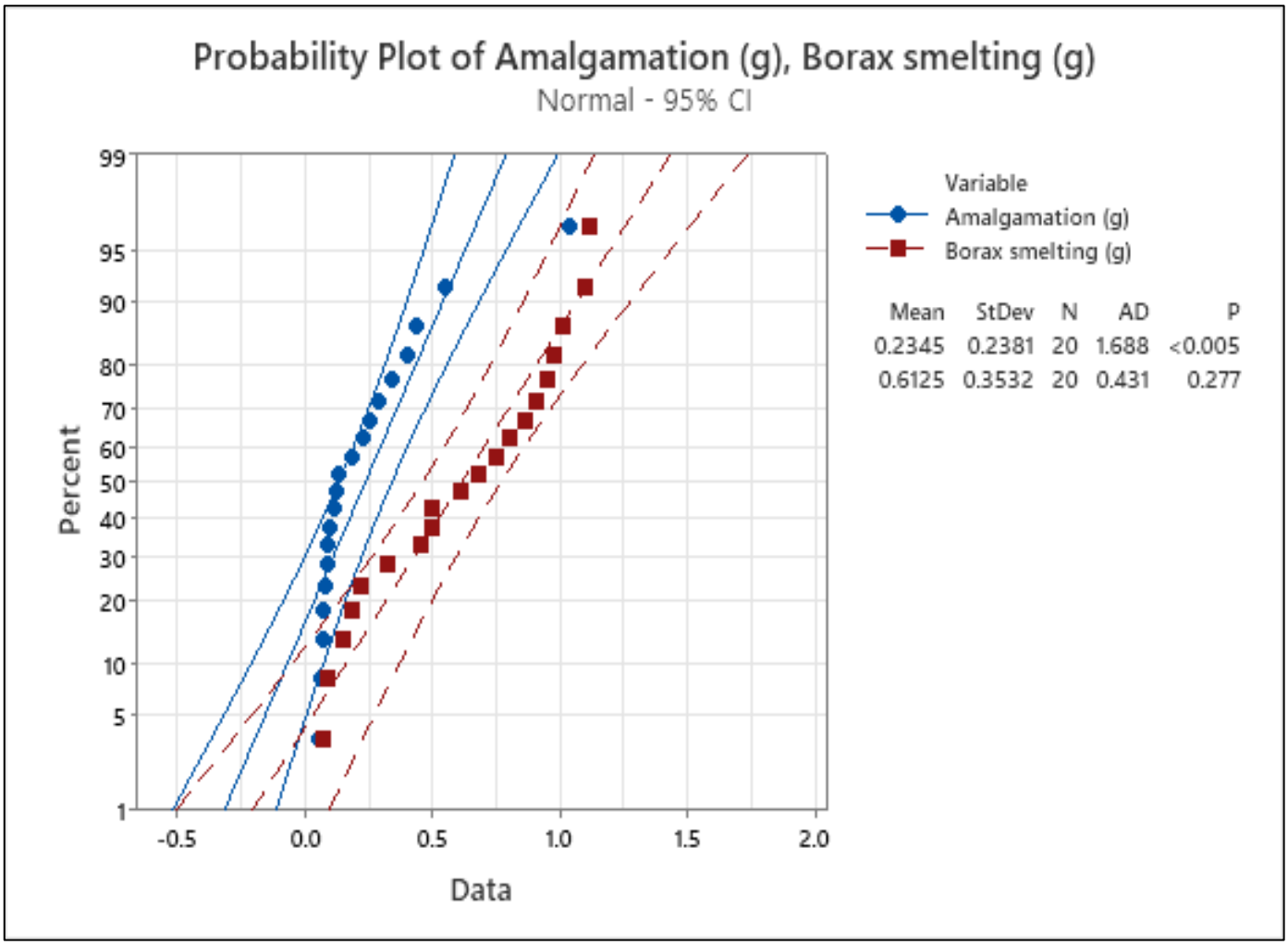

Fig 3 Combined Probability Plot of Amalgamation and Borax Smelting (G).

Wilcoxon test produced a test statistic of W = 210.00 with a p-value < 0.001, allowing the null to be rejected with confidence. The results of the Wilcoxon test showed that the difference in gold recovery of borax and mercury methods was statistically significant.

A one-way analysis of variance (ANOVA) was also conducted to see if there was a statistically significant difference between the performances of borax smelting across a range of ore types. Before conducting the ANOVA test homogeneity of variances was established using Levene's Test. The result of the ANOVA produced a p-value of 0.734 indicating that the difference in performance between quartz-vein-hosted and alluvial ores was not significant, and borax smelting performance is resilient and effective across differing geological settings.

Table 2 Wilcoxon Signed-Rank and One-Way ANOVA Test Results for Gold Recovery.

Statistical Test	Purpose	Test Statistic	p-value	Interpretation
Wilcoxon Signed-Rank Test	Compare gold recovery between borax and mercury	W = 210.00	< 0.001	Significant difference; borax yields higher gold recovery
One-Way ANOVA	Assess effect of ore type on borax performance	F = 0.122	0.734	No significant difference; borax works consistently across ore types

The statistical results indicate that borax smelting is not only higher recovery, but more robust under different geological conditions than mercury amalgamation. This reliability is important to ASGM communities where ore types and processing conditions may vary and are unpredictable.

Additional statistical analysis was completed to investigate the relationship between the two method results using Spearman's rank correlation coefficient. Analysis indicated a moderate positive correlation (r = 0.47), indicating that while both process responded to ore grade, borax has a better ability than mercury to extract additional fine or chemically locked gold. There are could be a number of combinations from the way mercury is used to its inert and non-reactive behavior with respect to certain mineral phases; therefore, borax and the utility of its flux behavior to remove unwanted silicates and oxides may allow free-gold separation to occur more effectively.

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Table 3 Spearman's Rank Correlation Results Between Borax and Mercury Recovery Methods.

Variable 1	Variable 2	Correlation Coefficient (ρ)	P-value	Interpretation
Borax Smelting Recovery	Mercury Amalgamation Recovery	0.47	< 0.05	Moderate positive correlation

This correlation suggests that in high-grade ore zones gold can be recovered using both techniques, however borax is more likely to recover a higher yield or recovery, particularly in low to medium grades. This feature of borax can also be of great operational advantage in ASGM contexts where ore grades have a high variability, and the ore grade is frequently not documented.

➢ *Visual Interpretation of Recovery Distributions*

This study utilized boxplots and histograms to visually display the gold recovery values obtained from mercury amalgamation and borax smelting methods across twenty paired trials for both ore types. These visual aids, effectively present the distribution, variability and outlying values of the dataset without excessive interpretation.

The boxplot presents a graphical summary of the central 50% of each dataset (the interquartile range) along with the median, minimum, maximum and outlying values. From the plotted results, it is clear that there is a much narrower interquartile range for the borax smelting method as well it has a higher median value, which suggests that the gold recovery results using borax were higher on average and more consistent across the trials.

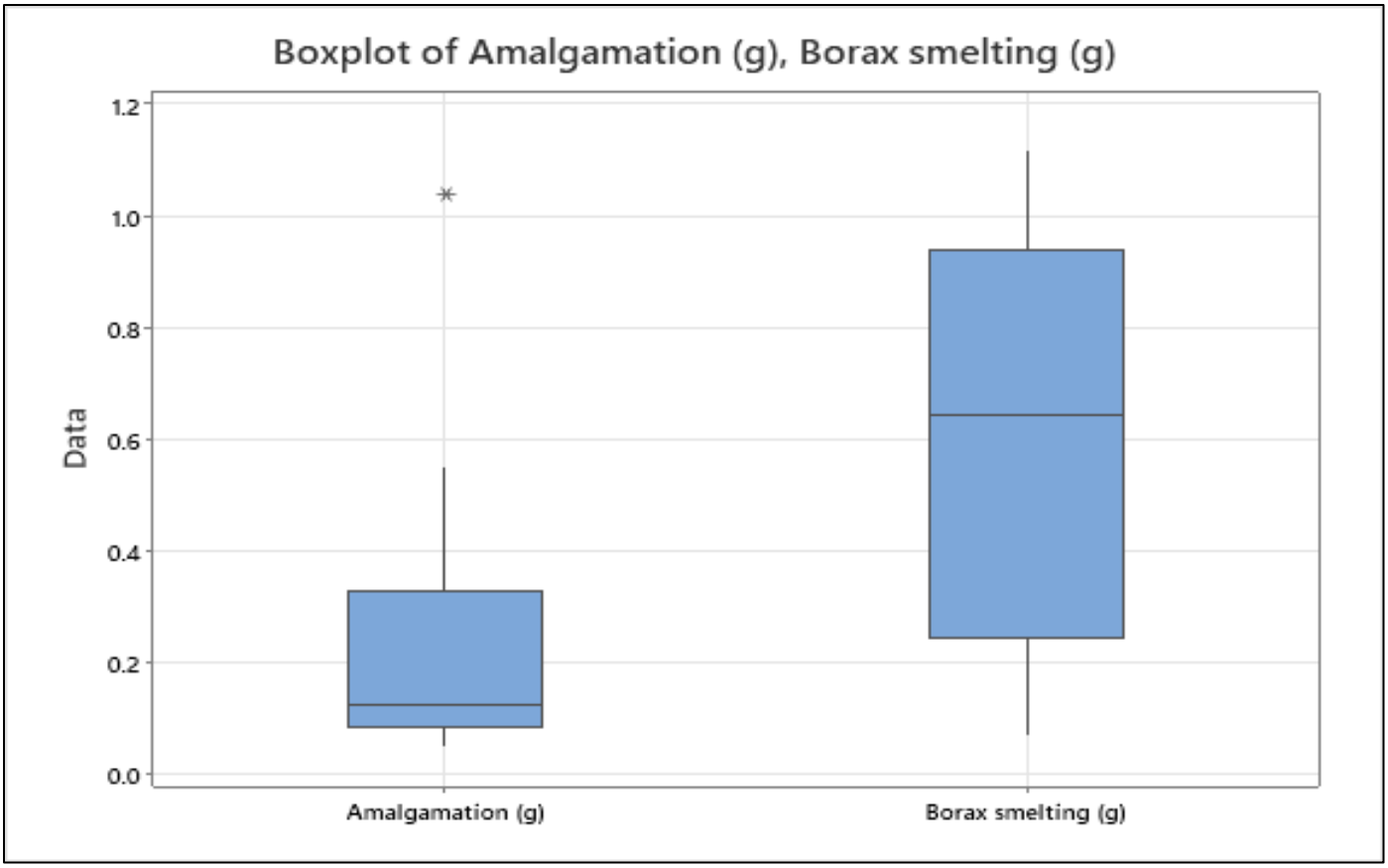

Fig 4 Boxplot Comparing Gold Recovery Distributions Between Mercury Amalgamation and Borax Smelting Methods.

In contrast, the mercury amalgamation data had a broader interquartile range with lower medians, and presented a large number of outliers at the low end, especially samples processed from alluvial placer ores. This result indicates a greater variability and instability in recovery efficiency for the mercury method as compared, to the borax smelting method.

In addition to the boxplots, histograms were produced to show how gold recovery values for each method were distributed over frequency. The histogram for borax smelting showed a distribution that was positively skewed or disproportionately to the right, clustered around larger recovery values while the histogram for mercury amalgamation showed a greater flatness with a long tail to the left leading to multiple low-value occurrences of gold recovery and higher variability. These patterns confirm that borax smelting achieved more consistent gold recoveries and achieved those recoveries within a narrower and higher range, while mercury amalgamation showed greater variability and greater occurrences of low yields.

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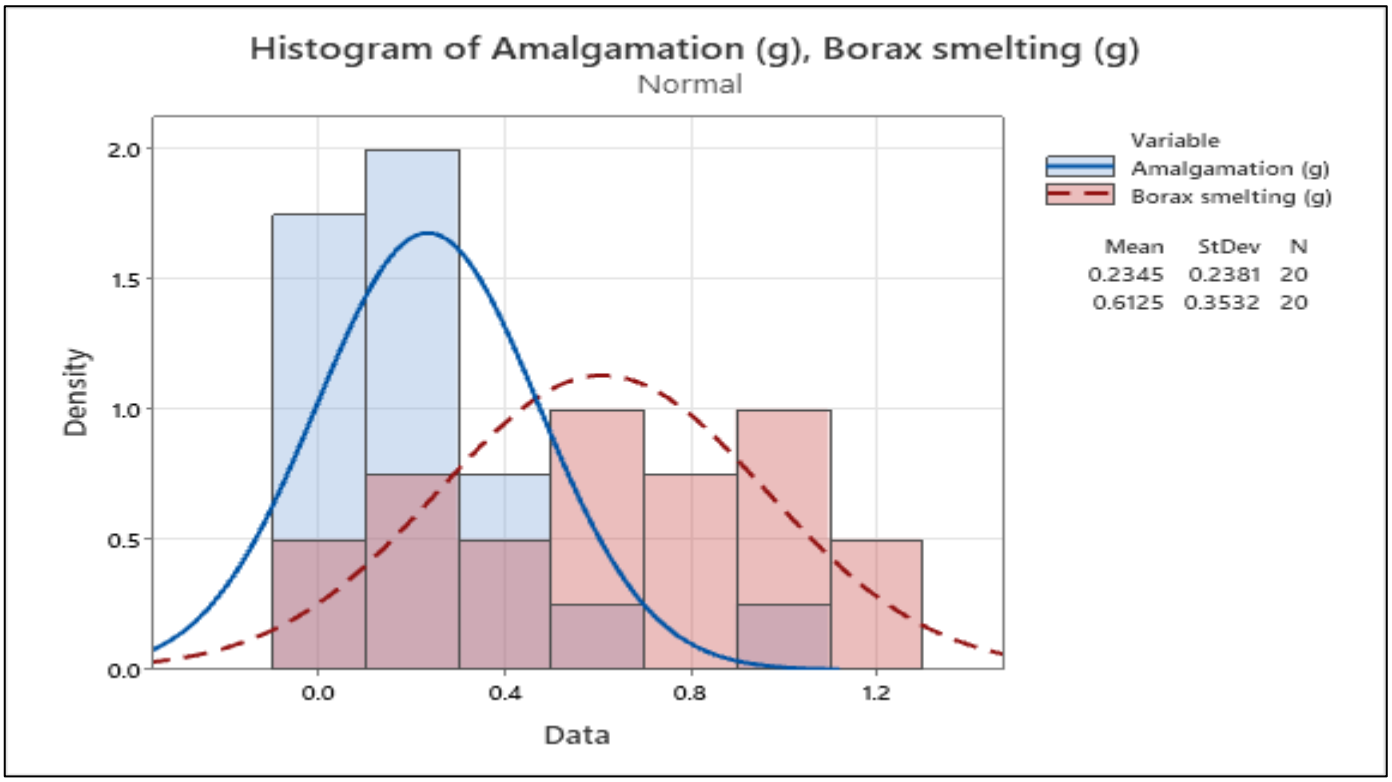

Fig 5 Histogram Comparing the Frequency Distribution of Gold Recovery Values Using Borax Smelting and Mercury Amalgamation.

The differences we observe in the distribution also emphasize the operational benefits of using the borax method in artisanal and small-scale gold mining (ASGM). For miners on small budgets and mining variable grades of ore, knowing that they will achieve consistent and repeatable results contributes to their increase in productivity and economic stability. In addition, increased consistent recovery performance will reduce the risk of unsuccessful possibly unprofitable runs, which is largely mitigated with mercury amalgamation because mercury amalgamation is very sensitive to the size of gold particles and interference from the other materials in each run. The visual observations agree nicely with statistics outlined earlier; reinforcing the conclusion that for ASGM, the borax method is simpler than mercury and more reliable and more effective as a method for extraction.

The lack of extreme outliers in the borax data suggests that the technique will continue to perform within expected limits even in less-than-ideal smelting conditions such as variable furnace temperatures, ore impurities, etc. This level of tolerance is particularly valuable for remote mining communities where environmental conditions and equipment are unpredictable, and processing of materials will always be variable in quality and consistency in time and exposure. Visualizing the data in this way strongly supports the adoption of borax as a preferred alternative to mercury in order to improve yield and reliability at the simplest level.

➢ *Environmental and Health Implications*

One primary concern for discontinuing the use of mercury in ASGM is because of its quite serious health and environmental risk. The mercury that is used in amalgamation is frequently released to the atmosphere as vapor when heated, or released into local water bodies, where it bio-accumulates in aquatic life and enters the food chain (Gibb & O'Leary, 2014; UNEP, 2013). Long-term exposure can lead to neurological disorders, kidney problems, and developmental problems, particularly in women and children in mining communities (Clarkson and Magos, 2006).

Borax, on the other hand, is a mineral compound that is non-toxic and unlike mercury, does not create toxic vapors, or harms the environment with residuals. The use of borax in gold smelting is environmentally safe and recognized as a best practice approach for sustainable artisanal gold production (Appel & Na-Oy, 2014). Moreover, there was no special safety gear or training needed, aside from what is expected for smelting. This makes borax a suitable and practical technology that would be appropriate for local use.

The environmental advantages will go above and beyond human health. Mercury-free tailings can be reused or discarded without the need for containment which reduces options for on-site remediation and environmental disturbance. In this regard, while using borax improves recovery, it supports Ethiopia's international obligations in the Minamata Convention on Mercury that seeks to phase-out or significantly reduces mercury use in ASGM practices.

➢ *Policy and Practical Implications*

The findings from this study create important implications for national policy, regional mineral development strategies, and local community actions. Borax smelting has been shown to be an effective, low-cost and environmentally safe alternative to mercury amalgamation,

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but applying these interventions in Ethiopia will require collaborative action from a variety of stakeholders.

In terms of government policy, the incorporation of borax smelting into national guidelines for mining and training materials for ASGM is necessary. The government's institutions such as Ministry of Mines, Regional Mining Bureaus, and Environmental Protection Authority able to offer technical support, outreach awareness and training workshops. Institutions working on behalf of NGOs working on behalf of health, environmental justice and rural livelihood development can provide vital assistance in supporting safe mining practices.

Training local miners and cooperative leaders in the use of borax is a necessary first step. Implementing borax projects on a pilot basis and subsequently rolling out the projects through mining unions and women's groups will allow for broad, inclusive uptake. Since sustainability can be strengthened by improving access to smelting equipment, creating local supply chains for borax and establishing markets for linking mercury-free gold to ethical buyers at premium prices can enhance sustainability.

V. CONCLUSIONS

This study presents a well-founded analysis of borax smelting as an alternative to mercury amalgamation in artisanal and small-scale gold mining (ASGM) in the Benishangul Gumuz Region, Western Ethiopia, and shows that borax smelting provides gold recovery that is more effective in terms of yield, and is more environmentally friendly and beneficial to human health compared to gold recovery by traditional mercury amalgamation.

The quantitative analysis showed that gold recovery was significantly better with the use of borax smelting (0.6125 g mean) than with use of mercury amalgamation (0.2345 g mean). The Anderson-Darling test showed mercury data were non-normally distributed while borax smelting data were normally distributed, and that both the Wilcoxon Signed-Rank Test ($p = 0.000$) statistically differed between the two methods, demonstrating the performance advantage of using borax smelting to recover gold.

The results of Levene's test ($p = 0.119$) and the one-way ANOVA ($p = 0.734$) show that gold recovery with borax smelting across different ore-type geology shows no differences based on quartz-vein-hosted primary ores and/or the alluvial placer deposits, which demonstrates versatility by removing geology as a limiting factor when estimating recovery using borax smelting. The versatility of gold recovery with borax smelting helps support the viability of an alternative method for ASGM, at both the level of implementation in local mines and also the potential for replication and scale-up in other local ASGM operations.

Beyond the technical efficiency, this paper has highlighted the environmental and public health benefits of using borax smelting. Processors can now recover gold without involving hazardous and toxic mercury that can harm human health, and damage ecosystems and communities, including in the forms of neurological damage and chronic respiratory diseases. Gold processors that smelt using borax would be technologically aligned with the goals of the Minamata Convention on Mercury which highlights the availability of alternatives to mercury for extraction of gold. These outcomes will advance Ethiopia's objectives for environmental sustainability yet also provide them with a pathway toward more responsible and resilient ASGM practices.

In summary the study concludes that borax smelting is a technically competent, economically viable, and environmentally sustainable method to recover gold. This method of extraction has the potential to fundamentally reduce the environmental and health risks associated with mercury while improving how much gold the small miner is able to recover. That being said, transitioning from mercury-based processing to processes involving borax will require action from all stakeholders including government policymakers, development partners, researchers, and mining communities. Implemented thoughtfully Ethiopia can nurture a cleaner, safer, and more productive ASGM sector with strong environmental obligations while concurrently meeting its national development targets.

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DECLARATIONS

- *Author Contributions*

Zeryihun Hailu Gebremariam: Conceptualization, methodology, field research, data curation, formal analysis, writing original draft and visualization.

Dr. Bisrat Kebede: Supervision, review and editing, validation,

- *Funding*

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➢ *Conflict of Interest*

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

➢ *Ethical Approval and Consent to Participate*

Informed consent was obtained from all individuals involved in the fieldwork. The study adhered to institutional and national ethical standards regarding the handling of hazardous materials and engagement with human participants.

➢ *Data Availability Statement*

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

➢ *Highlights*

- Borax was assessed as a non-toxic alternative to mercury for recovering gold.
- Field trials were carried out on quartz-vein and alluvial placer gold ores.
- Borax smelting had higher gold recovery rates than mercury amalgamation.
- The borax method lessened environmental and health hazards associated with ASGM practices.
- The results presented are in favor of mercury-free policies and safer gold extraction practices in Ethiopia.

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