Alternative Approach to Gold Extraction Using Modified Borax

Issac Adekunle, Joseph; Elizabeth J., Eterigho*+; Joseph O., Okafor
Department of Chemical Engineering, Federal university of Technology, Minna, NIGERIA

Comfort Temitope, Are
Department of Chemistry, Prince Abubakar Audu University, Anyigba, Kogi State, NIGERIA

ABSTRACT: *The extraction of gold in any part of the world is left in the hands of artisanal local miners who do this with the use of mercury which is considered to be a very hazardous chemical to humans and the biophysical environment. This research investigated the use of borax as a replacement for mercury in the extraction of gold from its ore. The sample used for the study was collected from Chanchaga mining site in Niger State. Calcination of the sulphide ore was done at a temperature of 600 °C in order to oxidize the sulphur content of the ore. The Borax in its modified form was used as a metal flux in the extraction process and this was optimized through the Box-Behnken experimental design method using Design Expert 7.0 software. The effect of temperature, the mole ratio of heavy mineral concentrate to borax, and time were studied at 800 – 1000 °C, 0.8 – 3.5, and 15-30 min respectively. Sieve, X-Ray Fluorescence (XRF), and carat analysis of the samples were carried out. The percentage yield of gold extract was 70.2 % at 900 °C, 30 min, and 0.8-mole ratio of heavy mineral concentrate to modified borax. The sieve analysis shows that visible gold liberation was achieved between 0.3 and 0.15 mm, and the X-Ray Fluorescence showed 88.7 % extract gold purity with 22 carats. This method can be a replacement for the current toxic method of gold extraction using mercury.*

KEYWORDS: *Gold; Mercury; Calcination; Borax; Extraction.*

INTRODUCTION

Gold is a chemical element with the Latin name Aurum, atomic number 79, symbol Au, a transitional metal in group 11, soft, yellowish, corrosion-resistant, the most ductile, and malleable metal. It is commonly found in rocks, alluvial deposits, and veins, it is chemically inert and does not react with water and air [1, 2]. It is resistant to most acid e.g. nitric acid, sulfuric acid, and hydrochloric acid, however, its dissolution occur in aqua regia (mixture of nitric acid and hydrochloric acid), hydrofluoric acid And hydrobromic acid. It is unaffected by most alkaline solutions e.g. potassium or sodium hydroxide. The Lydian Merchants (Western Turkey) were the first to produce and use the gold coin for money, the coin was known as ''electrum'' which consist of a mixture of 27 % silver and 63 % gold [3]. The ever-increasing global demand for gold can be attributed to its physical and chemical properties as well as its industrial applications in pieces of jewelry, space engineering, electronics, communications, decoration,

finance and medicine [4]. Several methods have been reported for the extraction of gold from its ore.

The cyanidation method is the method of gold extraction that employs the use of soluble sodium cyanide (NaCN) as a leaching agent. This method is a dominating technique [5, 6] and has been extensively used in gold extraction all over the world both on small and large scales [7]. This is due to the high yield of 99 % gold extraction by conventional leaching and an average of 50 to 80 % by heap leaching [6, 7]. The use of cyanide in gold extraction is associated with the release of a significant amount of cyanide into the environment. This can result in river pollution which can kill fish and other aquatic life [8]. *Edward* and *Paul* [9] pointed out that cyanide is acutely toxic to humans; gaseous or liquid hydrogen cyanide and alkali salts of cyanide enter the body through ingestion, inhalation, or absorption through the skin and eyes.

Aqua regia is a mixture of concentrated hydrochloric and nitric acid. It is commonly called royal water due to its ability to dissolve gold and is among the strongest chemical dissolver [6]. This method of gold extraction is efficient and can achieve 100 % extraction rate. However, the major setback to this method is that this chemical is unstable, extremely corrosive, and hazardous. Another disadvantage of this aqua regia method is that the inhalation of the vapor released during the process can lead to death immediately [6, 10].

Bromine and iodine are important halides used in the dissolution of gold; the two are similar in their reactions. These halides are a strong oxidizing agent with a higher dissolution rate than cyanide leaching. The major setbacks to these methods are high reagent costs, the difficulty of handling the reagents, health issues, and no industrial application [6]

The use of mercury in the gold extraction process has been in existence for centuries and this has been a source of livelihood for many small-scale miners in Middle and South America, South Asia, and Africa [11, 12], specifically in Nigeria. Mercury has been identified by the international community as an extremely hazardous chemical with a negative effect on human health and the biophysical environment [13, 14]. Mercury is a potent neurotoxin; it impairs and destroys the brain, nerve system, and other organs. Fetuses and children are at greater risk because mercury hinders the proper development of nervous tissue and can cause a mild reduction in intelligence,

and coordination, distortion of limbs, severe retardation, and in severe cases, death [15, 16]. The effects of fetus exposure to mercury may take months to years before appearing. After many years, the child may develop learning disabilities. During the gold extraction process using mercury, the liquid waste from the process is released into the environment (water, air, and soil). A significant amount of metallic mercury vapor is inhaled during the burning of amalgams in open pans by artisan gold miners as well as the locals around the mining sites. This could result in chest pains, kidney failure, pneumonia, coughing, and difficulty breathing [15, 17]. Mercury is released to the environment in liquid form during tailing while it is released to the environment in vapor form during the burning of amalgam. The aquatic life and soil are contaminated, up to two kilometers from the site [18].

In view of the challenges posed by previous methods of the gold extraction process, it, therefore, becomes necessary to research for an alternative to replace mercury in gold extraction. In this study, a novel method of gold extraction using modified borax (non-hazardous chemicals) as an alternative to mercury was examined**.** Boron is an important borax compound, a mineral, and salt of boric acid, with the chemical formula $Na_2B_4O_7.10H_2O$ or $Na_2[B_4O_5(OH)_4].18H_2O$. It is also known as sodium borate, sodium tetra borate, or disodium tetra borate. Powdered borax is white, consisting of soft colorless crystals that dissolve easily in water; boron is the main component of borax [19]. Borax as a flux will reduce the melting point of gold dust contained in ground ore, thus, after a direct smelting process, very pure and mercury-free gold was produced [11]. The method has several advantages compared to using mercury. One of the main advantages is that is mercury free, therefore, is environmentally friendly. Secondly, it does not require high investment in expensive equipment and the technique can easily be acquired by artisans. It also results in a higher yield compared to the mercury extraction process. Borax is a non-toxic substance and it is not in any way hazardous to the environment or health. Borax has been successfully tested and introduced for gold mining in China, the Philippines, Tanzanian, Bolivia, and Zimbabwe, however, it is yet to be practiced in Nigeria. Although, failure was recorded in Kalimantan (Indonesia) due to mineralogical composition [11, 12]. The sulphur content in Nigerian ore is a major setback to the use of borax for gold extraction;

however, this was overcome by the oxidation process in this study. The gold extraction in this study was carried out by calcination of the gold ore in order to reduce the sulphur content. The second stage involves the use of the Box-Behnken Design method of experimental design with Design Expert 7.0 for the optimization of gold extraction using modify borax. Chemical analysis of the gold ore and gold extract was carried out using XRF while the specific gravity method was used for the carat analysis. This study has established the extraction of gold from sulphide gold ore using modified borax at reduced temperatures.

EXPERIMENTAL SECTION
Materials

Representative samples of 200 g of the gold ores were collected from Chanchaga mining sites in Niger State. All the reagents used were purchased from Panlac Chemical Store, Minna, Niger State, Nigeria, and the reagents were of the analytical grade which is borax (99.5 %), potassium nitrate (KNO_3, 98.5 %), Silica (99.3%), sodium hydrogen carbonate (98.6 %). Distilled water, pH (Microprocessor (pH 212), Mechanical vibrator (HY-4 Vibrator), Furnace (Brainstead/Thermoline Corporation, Type1700) were gotten from Biochemistry Department, Federal University of Technology, Minna, Niger State, and Nigeria while jaw crusher was locally fabricated in Minna, Niger State of Nigeria.

Methodology
Physical processing of the ore sample

The ore sample was pulverized, ground, and sieved in order to enhance the easy liberation of the gold. The gold ore sample was crushed into fine particles using a jaw crusher. Sieve analysis was carried out with a set of eleven sieves. 200 g of ground samples were poured into the set of sieves and shaken for ten minutes and each of the retained masses by the sieves was collected, weighed, and recorded for further computation and plotting of the particle size distribution curve. The ground ore was washed with water over a sluice box in order to concentrate the minerals. The captured minerals by carpet were transferred into a container and a detergent was added to the mineral concentrate in the container in order to reduce the surface tension and promote better separation. The ore mineral concentrate was washed and panned several times with water in order to have heavy mineral concentrate. A dry

ceramic crucible was weighed and labeled M_1. A known gram of the heavy mineral concentrate was weighed into the ceramic crucible with weight recorded as M_2. This was heated in a furnace at a temperature of 600 ℃ for 20 minutes [20] and cooled in a desiccator. The weight of the cooled sample was determined as M_3 while the mass loss on ignition was determined as follows:

$$M ass\ loss\ on\ ignition = M_2 - M_3 \qquad (1)$$

Design of Experiment for gold processing

This study considered a three-level factorial design using Box-Behnken Design (BBD) for the extraction of gold with modified borax. The choice of BBD is due to its ability to accommodate a wider range of values between higher and lower levels of independent variables and gives satisfactory results under extreme conditions [21, 22]. 17 (2K(K-1) +Co) experiments were performed, where k is the number of factors which are temperature, time of extraction, and the mole ratio of heavy mineral concentrate to borax. Based on the preliminary study using a one-way optimization method, the effect of temperature, time, and mole ratio between heavy mineral concentrate and borax all have significant effects, hence extraction time was varied between 15 to 30 minutes, the temperature was varied between 800 and 1000 ℃ while the mole ratio between heavy mineral concentrate and borax was between 0.8 and 3.5. The BB design table for the coded independent variables of temperature, extraction time, and the mole ratio of heavy mineral concentrate and modified borax is presented in Table 1 while the temperature, extraction time, and the mole ratio of heavy mineral concentrate and borax for each experimental run are shown in Table 3.

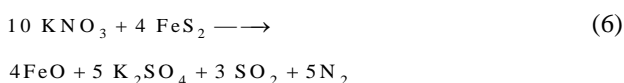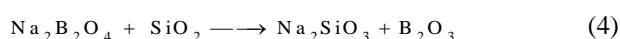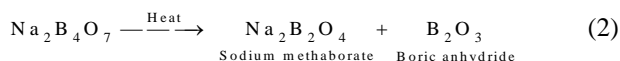### Extraction of gold from heavy mineral concentrate

A ceramic crucible was used as a reactor; this was preheated followed by the sprinkling of borax over the bottom of the crucible in order to prevent adherence of molten materials to its surface and shattering of the crucible during the extraction process.

Heavy mineral concentrate with a particle size between 0.3 and 0.15 mm, borax, and potassium nitrate (KNO_3) were weighed at a ratio 1:0.8:1 into the ceramic crucible. KNO_3, a strong oxidizing agent was added to further convert the sulphide into oxides thereby enhancing a better separation between the slag and gold. Silica (SiO_2) and sodium hydrogen carbonate ($NaHCO_3$) were also added

Table 1: Codes, ranges, and levels of independent variables of temperature, time, and mole ratio in BB design.

Symbols	Independent Variables	Coded Levels		
A	Temperature (ºC)	-1	0	1
B	Mole Ratio	800	900	1000
C	Time (Minutes)	15	22.5	30

at a mixing ratio of 1:0.8:1:0.25:0.25 (based on an earlier study by *Veiga et al.* [14, 23]) respectively in order to further increase the separation of gold from the slag. Silica was added to generate a matrix where the metals can be dissolved, while sodium hydrogen carbonate was used to control the pH (avoiding generation of gold chloride) and decrease viscosity. Equation 2 - 6 gives further explanation to an earlier report by *Abby et al.* [24] on the reaction mechanism involved in the removal of impurities from gold ore. The mixture in the ceramic crucible was placed in a furnace and heated at a temperature of 800 °C for 15 minutes. The content in the ceramic crucible formed slag and gold extract which was washed with trioxonitrate (IV) acid and water at 60 °C in order to separate the slag. The extracted gold was weighed and recorded; the yield is calculated by dividing the weight of the extracted gold by the weight of the heavy mineral concentrate. Other experimental runs were carried out according to the experimental design in Table 3.

$$Na_2B_4O_7 \xrightarrow{Heat} \underset{Sodium\ methaborate}{Na_2B_2O_4} + \underset{Boric\ anhydride}{B_2O_3} \tag{2}$$

$$ZnO + B_2O_3 \longrightarrow ZnB_2O_4 \tag{3}$$

$$Na_2B_2O_4 + SiO_2 \longrightarrow Na_2SiO_3 + B_2O_3 \tag{4}$$

$$10\,KNO_3 + 4\,FeS_2 \longrightarrow \tag{6}$$
$$4FeO + 5\,K_2SO_4 + 3\,SO_2 + 5N_2$$

Sample characterization

One gram of gold ore was transferred into a conical flask having 10 mL of distilled water and left on a mechanical vibrator for 30 minutes to equilibrate. After that, the pH of the mixture was measured three times using a pH meter and the average was taken within three minutes intervals. The chemical analysis of the samples was carried out by spectrometry XRF nitrogen 3000 using Cu-Zn method in order to have a wide variety of elements and sesquioxide.

The XRF was used to determine the concentration of the oxides and elements present in the ore samples. The refined gold sample was weighted and recorded as M_4. A beaker was filled with distilled water and it was placed on a weighing balance while the scale reading was at zero. The refined gold sample was submerged in the water on the weighing balance. The scale reading was taken and recorded as M_5.

$$\text{Specific Gravity} = M_4/M_5$$

$$\text{Chanchaga gold carat} = \tag{7}$$
$$\frac{\text{Amount of gold from XRF result X Highest gold carat}}{100}$$

$$= \frac{88.711 \times 24\,K}{100} = 21.29\,K$$

RESULTS AND DISCUSSION
The physical analysis of gold ore samples

The pH of ore samples helps to provide information on the acidity or basicity of the sample as well as the right process route to be adopted in the extraction process of the mineral constituents. The pH of the Chanchaga ore is 6.93. The dark-brown color of Chanchaga ore was largely due to the high percentage of iron and iron oxide in the ore.

Particle Size Analysis

The particle size distribution of gold ore from Chanchaga is presented in Table 2, this comprises the number of gold ore particles passing and retained through each of the sieves. During the analysis, it was observed that gold particles were clearly seen at 0.15 mm and 0.3 mm (more pronounced). Gold particles at other sieve sizes were not seen, this might be due to poor gold liberation at those particle sizes. Fig. 1 shows the plot of the cumulative passing of the particles against the particle diameter. According to Eq. (1), the coefficient of uniformity is 2.8 while the coefficient of curvature is 1.14 according to Eq. (9), both values indicate that the grain size of the gold ore span over a range and are well graded

$$\text{Coefficient of uniformity} = \frac{D60}{D10} \tag{8}$$

$$\text{Coefficient of curvature} = \frac{(D30)2}{D10 * D60} \tag{9}$$

Effect of calcination on heavy mineral concentrate

Out of 60 g of heavy mineral concentrate that was calcined, only 55 g of it was left after the calcination, the loss of

Table 2: Particle size distribution of gold ore.

Opening Diameter (mm)	Percentage Retained (%)	CR: Cumulative Retained (%)	Cumulative passing (%)
	$\dfrac{M - Sieve * 100\ \%}{M - Total}$		100-CR
5	5	5	95
3.35	1.55	6.55	93.45
2.36	6.7	13.25	86.75
2	3	16.25	83.75
1.15	11.9	28.15	71.85
0.85	6.45	34.6	65.4
0.6	9	43.6	56.4
0.425	8.3	51.9	48.1
0.3	7.8	59.7	40.3
0.15	15.6	75.3	24.7
0.075	10	85.3	14.7
Pan	14.6	99.9	0.1

M-Sieve: Mass of gold ore retained in the sieve, M-Total: Total mass of gold ore
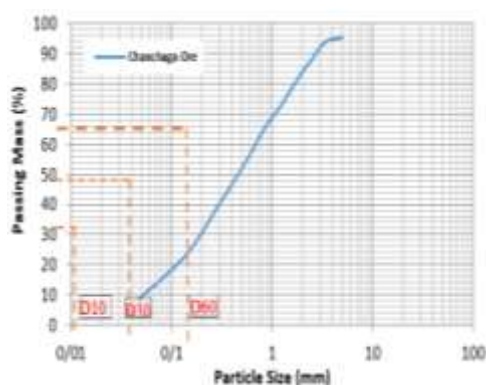
Fig. 1: Particle size distribution of gold ore sample.

of weight could be attributed to the oxidation of the elemental sulphur (equation 10). Calcination had a significant effect on the heavy mineral concentrate as it enhances the oxidation of the elemental sulphur, the ease of gold liberation, and the successful extraction of gold from a sulphide ore using borax [20].

$$S + O_2 \xrightarrow{\text{Heat}} SO_2 \qquad (10)$$

Second-order quadratic polynomial regression model and statistical analysis

Regression and graphical analysis of the data were carried out using Design-Expert 7.0. The yields of gold extracts were taken as the response to the design experiment. The response surface regression using the second-order polynomial Eq.(11) was used to analyze the experimental data obtained in this work

$$y = \beta_o + \sum_{i-1}^{k} \beta i x1 + \sum_{i-1}^{k} \beta_{ii}\, x_i^2 + \qquad (11)$$

$$\sum_{1i>j}^{k} \sum_{j}^{k} \beta_{ij}\, \mathcal{X}_i\, \mathcal{X}_j$$

Where; *y* represents the predicted variable (dependent), x_i and x_j are the uncoded independent variables, *i* and *j* are the linear and quadratic coefficients respectively, *βo* is the regression coefficient, *k* is the number of factors studied and optimized in the experiment. *Goyal et al.* [25] recommended the evaluation of the analysis of variance (ANOVA). The box-Behnken design was used to generate a quadratic regression model shown in Eqs (12 and 13) (based on the coded factors) from the experimental data.

Final Equation in Terms of Coded Factors

$$\text{Yield} = +73.27 + 4.10 * A + 7.00 * B - \qquad (12)$$
$$0.18 * C + 4.55 * A * B + 2.15 * A * C - 5.75 * B * C$$

Where *Y* is the gold extract (%), *A* is the temperature (ºC), *B* is the mole ratio and *C* is the time (minutes) respectively.

Table 3: Experimental and predicted data for the yield of gold extract from the Box-Behnken experimental design.

Run	(A) Temperature (^oC)	(B) Mole Ratio	(C) Time (Minutes)	Yield (%) Experimental	Yield (%) Predicted
1.	(-1) 800	(-1)0.8	(0)22.5	67.2	66.72
2.	(1) 1000	(-1)0.8	(0)22.5	68.8	65.82
3.	(-1) 800	(1)3.5	(0)22.5	65.4	71.62
4.	(1)1000	(1)3.5	(0)22.5	85.2	88.92
5.	(-1) 800	(0)2.15	(0)15	77	71.5
6.	(1)1000	(0) 2.15	(0)15	78.4	75.4
7.	(-1)800	(0) 2.15	(1)30	69.3	66.85
8.	(1)1000	(0) 2.15	(1)30	79.3	79.35
9.	(0)900	(-1)0.8	(0)15	56	60.70
10.	(0)900	(1)3.5	(0)15	88.2	86.20
11.	(0)900	(-1)0.8	(1)30	70.2	71.85
12.	(0) 900	(1)3.5	(1)30	79.4	74.35
13.	(0) 900	(0)2.15	(0)22.5	72.3	73.27
14.	(0) 900	(0)2.15	(0)22.5	72.4	73.27
15.	(0) 900	(0)2.15	(0)22.5	72	73.27
16.	(0) 900	(0)2.15	(0)22.5	72.4	73.27
17.	(0) 900	(0)2.15	(0)22.5	72.1	73.27

Final Equation in Terms of Actual Factors

$$Yield = +121.54188 - 0.095963 * Temperature - \qquad (13)$$
$$1.38235 * Time + 0.033704 * Temperature * Mole\ Ratio +$$
$$2.86667E - 003 * Temperature * Time - 0.56790 * Mole$$

The F-value for analysis of variance (ANOVA) was evaluated for the statistical significance of the model equation and the result indicated that the regression is statistically significant at 95 % confidence level. The model F-value of 7.60 for gold extraction implied that the model was statistically significant (Table 4). There is only a 0.29 % chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant (Table 5), therefore A, B, BC are significant model terms. Values greater than 0.1000 indicate the model terms are not significant, however, model reduction may be applied to insignificant model terms in order to improve the model. The value of

regression coefficient R^2 for the model is 0.8201, this indicates that the model is a representation of the experimental results.

The experimental and the predicted values for the 17 runs were compared in Table 3 and this shows the "Lack of Fit F-value" of 166.63 which implies the Lack of Fit is significant. There is only 0.01% chance that a "Lack of Fit F-value" this large could occur due to noise However the predicted yields are very close to the experimental yield.

Single effect process variables on gold yield (%)

Three process parameters of temperature, mole ratio, and time were chosen in order to evaluate their influence on the gold extraction. Fig. 2 represents the individual effect of temperature, mole ratio, and time on the gold extraction process. It can be seen that the yield increases steadily with an increase in temperature, this shows a positive effect on the yield. This could be due to the fact that the speed of the reaction for the dissolution of other components was greatly influenced by the temperature

Table 4: Analysis of variance (ANOVA) for the quadratic response surface model.

Source	Sum of squares	Degree of freedom	Mean square	F-value	Prob>F
Model	760.28	6	126.71	7.6	0.0029
Residual	166.76	10	16.68		
Lack of fit	166.63	5	46.47	82.00	<0.0001
Pure error	0.13	4	0.033	-	-
Correction	927.04	16	-	-	-

Adj R-Squared = 0.7122. R-Squared = 0.8201

Table 5: Coefficient of the model for gold yield.

| Factor	Coefficient Estimate	Standard Error	F-value	P-value	Remark
Intercept	73.37	0.99	-	-	-
A-Temperature	5.24	1.31	8.06	0.0176	Significant
B-Mole Ratio	7	1.44	23.51	0.0007	Significant
C-Time	-0.18	1.44	0.015	0.9059	Insignificant
AB	4.55	2.04	4.97	0.05	Insignificant
AC	2.15	2.04	17.26	0.3171	Insignificant
BC	-5.75	2.04	7.97	0.0183	Significant
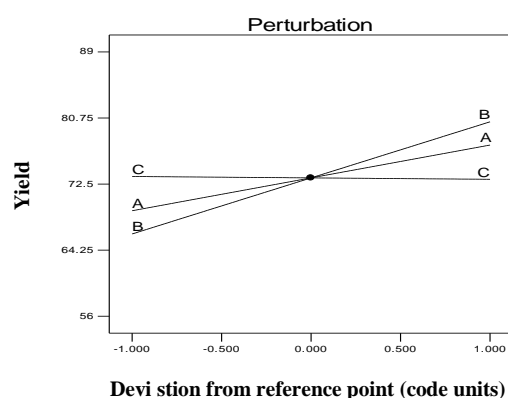
Fig. 2: Individual effect of temperature, mole ratio, and time on gold extract (%).

thereby resulting in higher extraction of gold. The yield increases also steadily with the increase in the mole ratio of gold ore to borax, this could be because more of the borax is available for reaction, and the borax acting as flux prevents the adherence of the extracted gold to the wall of the crucible and the impurities. The yield decreases slightly with increases in extraction time. This might be because increased extraction time causes the flux to dry off on prolonged heating and thereby making it difficult for the extraction.

Interactive effect of the process parameters on gold extraction

It can be seen in Fig. 3a that the yield increases as temperature increases which might be due to an increase in the reaction speed resulting in higher extraction, an increase in the mole ratio also increases the amount of borax that is available for extraction. At a constant extraction time constant of 22.5 minutes, the increasing effect of temperature shows that at the temperature of 800 °C and mole ratio of 3.5, 71.6 % yield was recorded while at the temperature of 1000 °C and mole ratio of 3.5, 88.9 % yield was recorded. There was a decrease in the yield at a constant extraction time of 22.5 minutes, 66.7 % yield was recorded at the temperature of 800 °C and mole ratio of 0.8 while 65.8 % was recorded at a temperature of 1000 °C and a mole ratio of 0.8.

Fig. 3b: shows the interactive effect of temperature and time on the extraction of gold from its ore. The yield increases significantly as the temperature increases while there was no appreciable increase in the yield when the extraction time was increased. The interactive effect was studied at a constant mole ratio of 2.15; the yield of 66.8 % was obtained at a temperature of 800 °C and time of 30 minutes while a yield of 79.3 % was obtained at a temperature of 1000 °C and 30 minutes of extraction time. The interactive effect was analyzed at a constant mole ratio
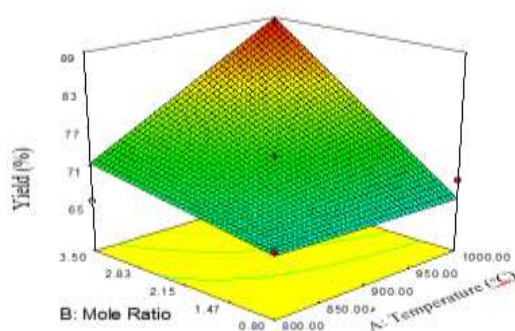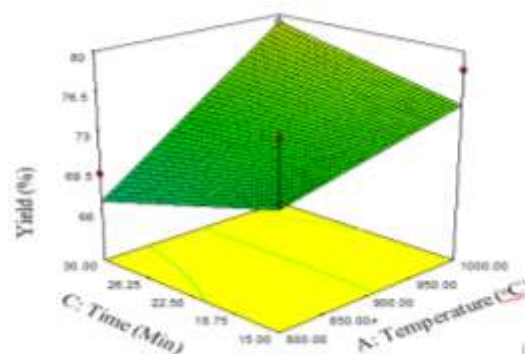
(a)   (b)

Fig 3: (a) Three dimensional (3D) plot of the interactive effect of temperature and mole ratio on yield (b) 3D plot of the interactive effect of time and temperature on yield.
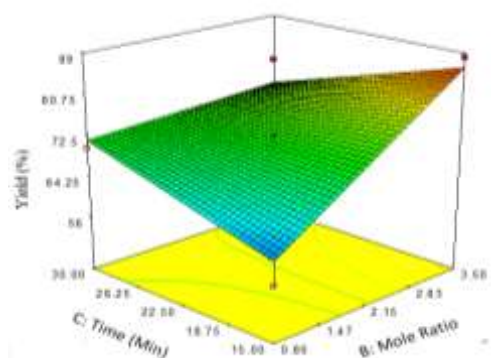

Fig. 4: 3D plot of the interactive effect of time and mole ratio on yield.

of 2.15, while the extraction time of 15 minutes was considered, 71.5 % yield was obtained at a temperature of 800 ºC and 74 % yield was obtained at a temperature of 1000 ºC

Fig. 4: is a contour plot describing the interaction between the time and mole ratio on the extraction yield of gold from its ore. There was a significant increase in the amount of extracted gold with an increase in mole ratio; this is because at a higher mole ratio more of the borax is available for the extraction of gold from its ore while the effect of time tends not to be significant. The interactive effect of the time and mole ratio was analyzed at a constant mole ratio of 2.15 and extraction time of 30 minutes, gold extract of 66.8 % yield was recorded at the temperature of 800 ºC while 79.3 % yield was recorded at the temperature of 1000 ºC. At a constant mole ratio of 2.15 and extraction time of 15 minutes, 71.5 % yield was recorded at the temperature of 800 ºC, while 75.4 % was recorded at 100 ºC.

Optimization Study

The optimization study by Design Expert was carried out by numerical method and it shows that minimizing temperature at 800 ºC gives a lower yield, while maximizing the temperature at 1000 ºC does not give much difference in yield compare to the yield at the temperature of 900 ºC. Therefore to save cost and energy, the optimum temperature was set at 900 ºC. Minimizing the mole ratio at 0.8 resulted in lower yield because only a small amount of the borax was available for the extraction while maximizing the mole ratio at 3.5 have a positive effect on the yield as more borax was available for the gold extraction and the excess borax prevent the adherence of the extracted gold particles to the wall of the crucible. Maximizing the extraction time does not have a significant effect on the yield, this might be due to the loss of the borax in vapor form on prolonged heating, while minimizing the extraction time have a significant effect on the yield as much of the borax was readily available for extraction. Another advantage of minimizing the extraction time is that the price of gold fluctuates with the price of dollars, while the value of dollars fluctuates with time, extraction at a minimum time helps to get the product to market on time in order to meet up with its high demand. Setting the yield at maximum, the interactive effect of the optimum process parameters of temperature, mole ratio, and extraction time helps to achieve an optimum yield of 86.2 % with desirability of 0.984 (98.4 %). The amount of gold recovery in this study is higher than the 1.23% recovery using the cyanidation method by *Ogundare et al.* [26], however, it is slightly lower than the 98.5% recovery using the agglomeration method by *Mlaki et al.* [18].

Characterization of gold ore and extract

The result of the XRF analysis is presented in Table 6 for both ore and extracted gold samples from Chanchaga. The results of the elemental composition of the ore samples show that the major elements in the sample are Si (10.822 %), Fe (7.737 %), Al (3.931 %), Ca (1.067 %), S (0.049 %), and Au (1.010 %, element of interest). 0.234 % of K is present in the extract while 0.175 % of K was present in the ore sample. This increment may be a result of the potassium nitrate used for the oxidation process; however, this does not have any negative effect on the economic value. The Chanchaga ore sample contains 75.473 % of Si, while 1.191 % of it was present in the extract; this shows that the washing and metal dissolution process was efficient. Considering the amount of silicon content in the waste, further purification process can be researched in order to meet the minimum purity level of silicon in the computer industry and the building of solar panels as Nigeria solely depend on the importation of silicon. If successful, this can also be a motivating factor for both government and investors to come into the long-abandoned mining sector. The Chanchaga ore sample contains 7.737 % of Fe, while 0.049 % was present in the extract. The significant decrease in the Fe content was due to the washing and metal dissolution process. The result in Table 6 and Fig. 5 show that Chanchaga (1.01 %) has higher percentages of gold compared to 0.0019 % gold in Osun, Nigeria [26], O.0019 % in Indonesia, and 0.0018 % of gold in Canakkale, Turkey [27]. This higher percentage of gold content in the ore samples from Niger state could offer a better income for both Government and the local miners if appropriate methods are used for the extraction, separation, and purification. This high percentage composition of Au in the extract is an indication of the high economic value of this sample; this can be an encouragement to both government and investors. However higher purity can be achieved if the sample is subjected to a further purification process.

The presence of sulpur in the ore could make the extraction of the gold unsuccessful using borax [12, 15, 28] however, this was overcome by calcination [15] of the ore followed by oxidation [14]. The low detection of sulphur in the extract is an indication that 0.049 % of the sulphur in the ore must have undergone an oxidation process and thereby resulting in the higher purity of the extracted gold.

Table 6: XRF results of ore and extracted gold samples of Chanchaga gold mine.

Element	Chanchaga (Raw Sample) (%)	Chanchaga (Extracted) (%)
Si	75.473	1.191
S	0.049	<LOD
K	0.175	0.234
Ca	1.067	<LOD
Ti	0.576	0.05
V	0.027	<LOD
Cr	0.02	<LOD
Mn	0.059	<LOD
Fe	7.737	0.049
Cu	<LOD	0.009
Zn	0.013	0.013
As	0.002	<LOD
Sr	0.005	<LOD
Zr	0.008	<LOD
Ag	<LOD	0.041
Ba	0.032	<LOD
Au	1.01	87.711
Bal	3.931	10.71
Total	99.996	99.99

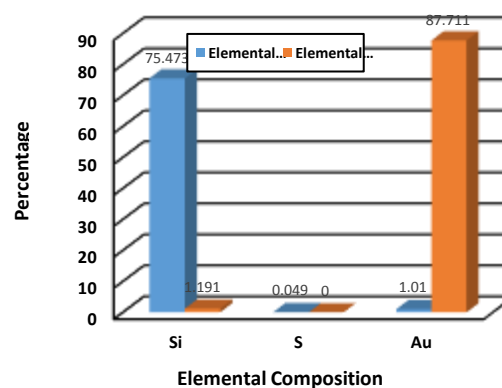**LOD: Low Detection,   *Bal: Balance; amount of elements that could not be detected*

Fig. 5: Essential elements of Chanchaga gold ore and extract gold.

Table 7: Oxide composition using X-Ray Fluorescence (XRF) (Cu-Zn Method).

Oxide Content	Chanchaga Ore (%)	Chanchaga (Extract) (%)
CuO	0	0
NiO	0	0
Fe_2O_3	11.063	0.07
MnO	0.076	0
Cr_2O_3	0.029	0
TiO_2	0.962	0.008
CaO	1.494	0.668
Al_2O_3	7.43	0
MgO	0	0
ZnO	0.016	0.016
SiO_2	23.16	2.548
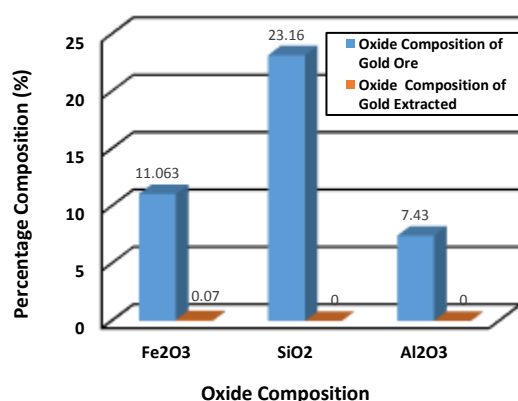
Fig. 6: Major oxide composition of Chanchaga gold ore and extracted gold.

The result of the oxide composition of the ore and extract samples from Chanchaga is presented in Table 7, while Fig. 6 shows the plot of the major oxide composition. The result clearly shows that there was a significant reduction in the oxide content of the extract which could be attributed to the efficient processing of the ore. 11.063 % of the Fe_2O_3 was present in the ore, while 0.07 % of Fe was present in the extract. During the extraction process, 7.43 % of Al_2O_3 was removed from the ore. Out of the 23.16 % of SiO_2 present in the collected ore, only 2.548 % of it was left after the extraction process.

Gold Carat

The result of the carat analysis showed that the gold extract has a specific gravity of 18.18 which correspond to the 22-carat (22 k) on the gold density table. The value of 22k is slightly above the 21.29 K obtained from the estimate from the XRF result. However, at the time of this study, no report was found on gold carat analysis.

CONCLUSIONS

The high percentages of gold in ore samples from Chanchaga (1.01 %) are an indication of the potentiality of the ores for gold mining. The high percentage of gold with low sulphur content shows that the extraction of gold from the site can be done by an environmentally friendly method with modified borax compared to the current non-environmentally friendly method of mercury extraction in Niger State. Visible gold liberation was recorded at 0.3 and 0.15 mm. A second-order quadratic model that could predict the yield of gold extract from the process parameters considered in this study was developed. The ANOVA results from established temperature and mole ratio as the significant process parameters while extraction time was insignificant.

The gold extraction yield of 70.2 % was achieved at a temperature of 900 ºC, 0.8 mole ratio, and 30 min extraction time. The result of the carat analysis shows that the gold extract from Chanchaga has 22 K which is close to the estimated 21.29 K from the XRF result, and both results are within the acceptable set gold carat of 24 by the international gold marketers.

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