Development of an Economic Cost Model for Gold and Associated Minerals Using Economic Analysis and Artificial Intelligence Approach

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ORIGINAL RESEARCH

Abstract— Limited accuracy due to complex geological processes, insufficient data granularity, and challenges in predicting market dynamics impact mineral forecast models. In order to develop a cost-based model for gold and related minerals in Birnin Gwari (Kaduna State) and Kagara (Niger State), this study is being carried out in Nigeria. The created concept aims to increase the profitability and economic viability of open-pit mines operated by craftsmen and mining investors. By maximizing mine life cycles and preventing the early closure of mining sites, this was intended to encourage the best recovery rates. This study used economic and artificial neural network (ANN) modeling methods to create a cost-based model for ten gold-associated minerals. The coefficient of correlation (R^2), root mean square error (RSME), and variance accounting factor (VAF) were used to assess the created model's correctness. The model evaluator demonstrates that the proposed cost-based models are economically viable and the quantitative results are as presented in Equations (14-23). The cost-benefit connection between gold and the ten related minerals was also determined using a least-squares regression analysis. According to geochemical results, the average values of gold and related minerals in the study region range from 4.87 g/t of gold (Au), 1.501 g/t of copper (Cu), and 187.13 g/t of iron (Fe) in Birni Gwari to 2.29 g/t of gold (Au), 1.358 g/t of copper (Cu), and 173.75 g/t of iron (Fe) in Kagara. In Birnin Gwari, the equivalent financial estimations are N876,600 for Au, N60,040,000 for Cu, and N1,129,375 for Fe, and N5,780,000 for Au, N49,500 for Cu, and N363,060,000 for Fe in Kagara. The model's scope demonstrates that running a single mineral can result in low recovery rates and a loss of profit margin; thus, the model's application to all open pit mines is relevant as a reference for profit margin cash flow.

Keywords— Gold, Nigeria, Mining industry, cost-based model, Artificial intelligence.

1 INTRODUCTION

Gold is a precious metal and occurs naturally in various forms across the Earth's crust. It is primarily found in veins and lodes within rocks and ore deposits (Du et al., 2023). As mentioned by Meyer (2023), gold deposits are formed through geological processes such as hydrothermal activity, where hot water carries gold-bearing minerals to cooler environments, allowing gold to precipitate out. Placer deposit is formed by erosion and weathering, this is another common occurrence of gold (Lalomov et al., 2017). According to Gbolagade et al. (2023) findings, it was mentioned that the elemental composition of other associated minerals existing with gold is a significant asset that defines the amount of additional economic contribution that can be obtained from the gold tailings. Major gold-producing regions include Australia, South Africa, the United States, Russia, and China (Manohar and Guntur, 2021). The mining of Gold involves extraction through methods like underground mining, open-pit mining, and heap leaching, contributing to its significance in global economies and trade.

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Additionally, gold mining and related industries create jobs and stimulate economic activity, further bolstering a country's financial stability and development. Birnin-Gwari and kagara gold deposit sites are within the Kushaka schist belt of northwestern Nigeria (Obaje, 2009). Kwaga site is a recent discovery by artisanal miners following the extensions of the Birnin Gwari mine. Birnin Gwari gold mineralization are within a series of metasediment that lie in a number of isoclinal fold structures trending N-S. The strong foliation is parallel to the axial plane of the fold's gold-bearing quartz bodies (echelon veins, boundins, silicified phylilites are hosted by series of narrow shear zones, which developed along the main (S1) Schistosity and antifolded carbonaceous (graphitic) phyllites. Birnin Gwari Gold reef system is about 7 km long, while the Kwaga reef system extends for about 3 km, and both structures are sub-regional extent disrupted and displaced by the Kalangai fault. Core drillings of outcrops have provided relatively gold-quartz reefs and their lineament rocks from which the geochemical characteristics of the Birnin Gwari Mineralization are studied (Garba, 2002).

In Nigeria today, mining sector is one of many with tremendous growth prospects in the country. Nevertheless, according to the Nigeria Bureau of Statistics the sector contributes only 0.5% to the country's Gross Domestic Product (Onwe, 2013). Moreover, with a contribution of 0.3% to national employment and 0.2% to total export, the sector's potential for local employment creation and revenue diversification is far from being fully realized in Nigerian. It has been discovered that numerous associated minerals that come along with gold during exploitations, are either abandoned as waste or sent abroad as gangue/concentrates where thorough beneficiation and refining takes place (Alaba, 2017). Meagre amount is being remitted here in Nigeria while the foreigners take advantage of crude method of our beneficiation and refining to their own financial advantage. Ousman and Mouna, (2015) in their analysis, shows that gold mining industry in Africa exhibits significant economies of scale. In other words, the unit cost of production falls significantly as mines get larger. In Birnin Gwari and Kagara, nearly everything is done manually and with primitive implements by the local miners, but the local miners seem unaware of their hard labour since they make contented earnings from their work. It is of economic important to develop an economic cost model that will be a guide at the preliminary stage of gold exploration that will capture all minerals that are associated with gold and the financial value that will be generated at the time of mining and beneficiation. Although artisans and illegal miners are predominantly gold workers in Birnin Gwari, and Kagara gold mines, but they do not have the knowledge of any associated minerals with gold which lead to waste and economic loss (Gbolagade *et al.*, 2023). Therefore, there is need for a model that will serve as a template for economic cost evaluation of gold and associated minerals at the time of exploration before full mining operation is commenced. This will add to the value chain of these associated minerals thereby encouraging establishing of beneficiating plants and increase the socio-economic value of the study areas. Employment opportunities will ultimately increase, foreign exchange will be saved from importation and it will add to the Gross Domestic Products (GDP) of the country. This will also strengthen the value of our currency, thereby attracting more investors into the country. In addition, many gold mines that have been exhausted and abandoned without further reckoning to some associated materials might be revisited. This study focused on the value-added revenue development model for gold and associated minerals which will serve as a template when carrying out explorations before full exploitation is started. The result from this research provides guide to both potential investors into solid mineral sector and to the economic diversification agenda of the Federal Government of Nigeria.

2. LITERATURE REVIEW

2.1 Gold Occurrence In Nigeria

Since the departure of Colonia masters, the Nigerian Gold fields has experienced intense artisanal workings which target both the primary gold-quartz reefs and their associated alluvial occurrences (Azubike, 2011). Mineralization associated with lead ores has recently observed in Zamfara state, suggesting the possibility of different types of gold deposits in the state (NGSA, 2010). Gold mineralization is controlled by deep seated curvilinear transcrustal fracture system. These deep-seated fracture systems, Anka-Yauri-Iseyin (AYI) and Kalangai-Zuru-Ifewara (KZI) are believed to have served as conduits to the subsidiary fractures which are linked to these major fractures and form sites of gold deposition (Garba, 2000).

The Nigeria's gold is found in alluvial and eluvial placers and primary veins from several parts of supracrustal (schist) belts of the northwest and southwest of Nigeria (Obaje, 2009). The major commercial gold deposits and some smaller occurrences in Nigeria are shown in Table 1. All are associated with the schist belts of northwest and southwest Nigeria (Obaje, 2009).

Table 1: State and Community of Gold Occurrence in Nigeria (After Obaje, 2009)

STATE	VILLAGE LOCATION
Zamfara	Anka, Maru, Malele
Kebbi	Bin Yauri, Mararaba, Waya, Rafin Bakin Dutsi, Laka and Gerin Hawal
Kaduna	Tsohon Birnin Gwari and Kwaga
Niger	Gurmana
Kogi	Okolom-Dogondaji, and Egbe-Isanlu Area
Kwara	Bishewa, Ologomo, Agboro, Korobiri, Degeji, Ndanaku, Mari, Oputa, Lokomosi, Bichi, Gbajubo, Giloadi and Birnin Ruwa
Osun	Iperindo (Ilesha)
Ogun	Ajegunle-Awa
Oyo	Shaki and Irawo areas
Ekiti	Ijero
Cross River	Oban Massif area

2.2 Previous Research Work Gold And Associated Minerals

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A number of researchers across the world have carried out investigations on Gold. However, investigations on value added to be derived from associated gold minerals and economic cost models are limited (Melodi *et al*., 2023). Alaba, (2017) found out that Trace Metal (TM) in Gold Ore Sample at Horo Mine Site, Zamfara state, include Lead(pb),17.11 ppm, Cadmium(Cd), 0.04 ppm, Copper (Cu), 8.10 ppm, Iron(Fe), 3.52 ppm, Zinc(Zn), 1.29 ppm, Manganese(Mg), 0.89 ppm, Nickel(Ni), 0.36 ppm, and Chromium(Cr), 0.35.The result of the finding is the concentration of lead in gold mines and its adverse effects on human and living organism. Melodi and Ganiyu, (2019) carried out research on Socio-Economic Assessment and Profitability of Artisanal Gold Miners in Niger State, Nigeria. In as much as there is profit in gold mining, much more is lost when optimum utilization of methods is not explored. The results only centered on only single concentrate output (gold). Tirima *et al*, (2016), Abdulkareem *et al*, (2015), Buba and Aboyeji (2015) were the previous researchers who had worked on the presence of heavy metals in association with gold. However, the results of the findings centered on the adverse effects of these metals on the habitants and environment. Lane *et al*, (2006) develop a prototype economic optimization model (EOM) for gold mines using Microsoft Excel. The success of this initiative resulted in Gold Fields commissioning a prototype 'Mini EOM' for all the South African operations to test economic viability and optimize the Net Present Value (NPV) of the life of mine reserve plans and projects. But the optimization model is limited to gold alone.

Potentials of gold mining and extraction methods have been extensively studied by several researchers and authors as well. Some authors wrote about the process of mining of gold or gold ores from the ground.

Barry and Xinwu, (2020) wrote about sluicing which involves larger commercial placer mining operations employing screening plants, or trammels, to remove the larger alluvial materials such as boulders and gravel, before concentrating the remainder in a sluice box or jig plant. These operations typically include diesel powered, earth moving equipment, including excavators, bulldozers, wheel loaders, and rock trucks. Ako *et al*; (2014) suggest that Phytho mining which is the use of hyper accumulating plants to extract a metal from soil with recovery of the metal from the biomass will yield to return on economic profit. Adesida *et al;* (2017) wrote extensively on the effect of capital and operating cost on the Aggregate production in some selected quarries in North-Central Nigeria. In the research, this has much impact on the gold that is predominantly mineralized at pegmatite shist because of circles of operation which includes drilling and blasting. Drilling and blasting operations must be carried out before run off mines are hauled to the beneficiating plant.

However, none of the authors wrote about the development of any economic cost model for some of minerals that always regarded as gangues in the process of gold extraction or beneficiation. It is on these limitations this research work is based on to explore, geo-physically, geochemically, geologically and determine the mineral composition of gold and associated minerals to develop the cost model for gold and all associated minerals. This research focused on the economies of gold and associated minerals in the study areas. The economic cost model developed for gold and associated minerals will be a guide during exploration before commencement of full mining operations. Hence, it will be of benefit for small- and large-scale operators of gold mineral. Artificial neural network (ANN) had been utilized in different field over many years (Taiwo et al., 2024; Taiwo and Adebayo, 2023)

. Taiwo et al. (2023a) and Taiwo et al. (2023b) applied ANN algorithm to predict limestone and small-scale dolomite blast production capacity. The findings show that ANN is a powerful algorithm for mine blast improvement. Also, Taiwo and Adebayo (2023) develop BlastFrag optimizer software using ANN algorithm with both blast controllable and uncontrollable parameters. They concluded that ANN provide good prediction result for blasting and in mining operation.

3. Materials And Methodology

This section presents the methodology used for sample collection, preparation, and for the chemical composition analysis.

3.1 Study Area Description

The research site is about 13 kilometres north of Kagara and Birnin Gwari Village in Nigeria. The terrain is mostly undulating, with moderate hills divided by plains with flat soil cover. The geological area of the case study area is depicted in Fig. 2. Systematic alluvial soil sampling techniques were utilized in this work to collect representative soil parts for geochemical investigation as shown in Fig. 2 and 3. Each gold-bearing sample's compositional constituents were determined using fire assay (FAA) and multi-element analysis (MEA) procedures developed by Masasire et al. (2021). SGS South Africa (PTY) Limited (Randfontein) Laboratory conducted the analysis. X-ray analysis was also employed to generate a diffraction pattern with an appropriate wavelength for sample elemental assessment using the Gibbs (1965) approach. Field samples (soil samples, alluvial deposit samples, and rock samples) were pulverized to 50 m and exposed to an incident beam. A total of 155 questionnaires were issued at random to the workers and management of the various artisanal gold mining sites in Birnin Gwari and Kagara to collect data on the amount of gold (g/t) mined daily. Cost of blasting pegmatite gold host rock per month, cost of drilling accessories used, cost of explosives used, cost of plant and equipment maintenance, and cost of labour. The information gathered was used to calculate the overall

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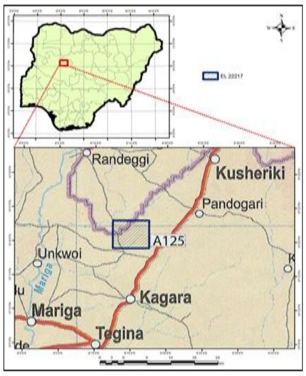
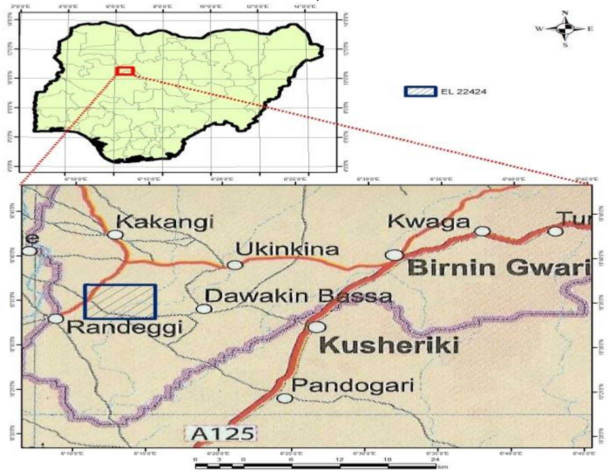
variable cost and the cost of producing one gram of gold. The average selling price of gold concentrate per gram was also gathered.



S/No	Longitude	Latitude
1	6° 12′ 30″	10° 19′ 00″
2	6° 12′ 30″	10° 23′ 00″
3	6° 17′ 30″	10° 23′ 00″
4	6° 17′ 30″	10° 19′ 00″

a)



b)

Fig. 1 Geological Map of the Study Area in a) Kagara and b) BirniGwari

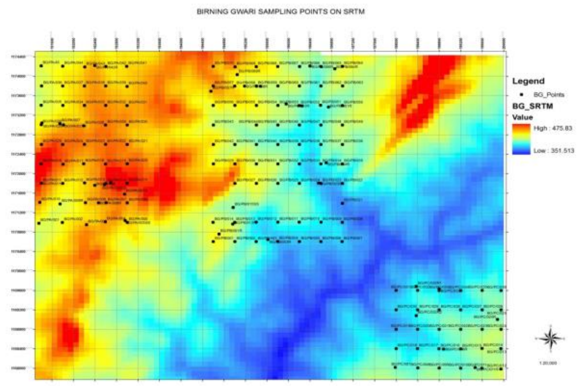


Fig. 2: Sampling Points on SRTM at Birnin Gwari

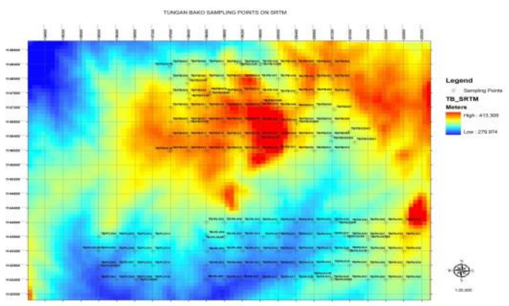


Fig. 3: Sampling Points on SRTM at Kagara

3.2 Artificial Neural Network (ANN) for gold associate Mineral worth prediction

Results evaluated from exploration of gold and associated minerals were used to develop economic cost model using cost accounting methods. Furthermore, quantitative model was developed using 1-7-1 architectural Artificial Neural Network (ANN) models for the prediction of economic cost of ten (10) gold associated minerals identified from the chemical analysis. The quantity of gold recovered was used as the model dependent variables. However, capital and operation cost for gold exploitation dependent parameters were also computed using the U. S Bureau of mines Cost Estimation System (CES) following the procedure of Camm (1987). Least squares regression method was used to modify cost index proposed by Camm (1987) for both capital and operating cost as shown in Equations 1-3.

The life and daily capacity of mining operations were determined using Equation (1) based on Taylor (1978).

$$C = \frac{(T)}{(L \times dpy)} \quad (1)$$

Where L is mine life in years; T is total tonnage in tons of the ore mined; dpy is operating days /yr.

The total ore recovery was calculated using the Equation (2).

$$T = (rt) \times (rf) \times (1 + df) \quad (2)$$

Where rt, is the deposit reserve tonnage in tons, rf is recovery factor for the mining method, df is the dilution factor.

Substituting for L using Taylor's rule (1978)

$$L = 0.2(T)^{0.25} \quad (3)$$

Mining capacity, C in tons/d was determined using Equation (4).

$$C = \frac{(T)}{(260 \times L)} = \frac{T^{0.75}}{52} \quad (4)$$

3.3 Model Error Analysis

Validation results of the models were carried out using the coefficient of correlation (R^2), root mean square error (RSME), and variance account for (VAF). (Eq. 5-7). When R^2 and VAF show high value, it indicated good correlation with low variance between the predicted and measured quantities of all the associate minerals. Also, low RSME values shows that the predicted values of the associated minerals are closer to the measured values. The extracted final equation in this study was complemented with both capital and operating expenses. The cost of operation and other capital expenditures were factored into the proposed model.

$$R^2 = \frac{\sum_{i=1}^{r}(\alpha-\beta)^2 - \sum_{i=1}^{r}(\alpha-\omega)^2}{\sum_{i=1}^{r}(\alpha-\beta)^2} \quad (5)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\alpha-\beta)^2} \quad (6)$$

$$VAF = \left(1 - \frac{var(\alpha-\omega)}{var(\alpha)}\right) \times 100 \quad (7)$$

Where α is the measured associate mineral quantity in g,

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ω is the ANN predicted associate mineral quantity in g.

4. Results and Discussions

4.1 Mineral composition Analysis Result

The summary of the chemical composition analysis is presented in Table 2. The gold (Au), aluminum (Al), copper (Cu), iron (Fe), lithium (Li), magnesium (Mg), nickel (Ni), thorium (Th), uranium (U), and lead (Pb) compositions in the analysis samples range from 0.01-0.19 g/tonne, 0.48-4.91 g/tonne, 5.6-113 g/tonne, 0.51-7.99 g/tonne, 2-30 g/ton, 0.03-0.73g/tonne, 156-3080 g/tonne, 0.25-88.4 g/tonne, 2.6-33.3 g/tonne, 0.53-5.53g/tonne, 0.2-189g/ton, respectively. Skewness is a measure of the symmetry or asymmetry of the data distribution, and kurtosis measures whether the data is heavy-tailed or light-tailed in a normal distribution.

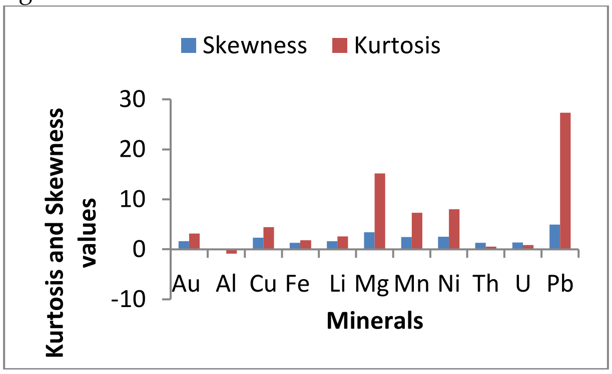

Fig.4. Relationship between each associate mineral data distribution order

The aluminum dataset distribution is peaked and possesses thick tails, as shown by the negative skewness and kurtosis. All other mineral datasets distributions pushed towards the right side, as indicated by the positive skewness and kurtosis (see Fig. 3).

4.2 Development of Economic Cost Benefit Model using Accounting Cost Models

Figures 5 and 6 show modeled Capital and Operating costs. This shows that capital expenditures are required for maximization of gold and associated minerals while operating cost are almost the same either operating molybdenum or multiple mining concentrates. The developed models for predicting the economic impacting factors (Labour Mining cost, Equipment cost, bits cost, fuel cost, and Explosive and drilling cost) are presented in Equations 8-13.

Figure 7 show the Exploration and Development Cost Index Model while Figure 8 shows the Mining Labour Cost Model. The performance accuracy of the developed linear models was evaluated using correlation coefficient. The validation shows that the entire developed model results as correlated with the actual values have a very high performance with 90-99% accuracy.

$$EDC = 14.58 \times Yr - 28790 \quad (8)$$
$$LMC = 0.456 \times Yr - 896 \quad (9)$$
$$EQC = 4.57 \times Yr - 8973 \quad (10)$$
$$BC = 4.443 \times Yr - 871.5 \quad (11)$$
$$FL = 3.357 \times Yr - 6593 \quad (12)$$
$$EC = 4.350 \times Yr - 8533 \quad (13)$$

Where; EDC is exploration and development cost, LMC is Labour Mining cost, EQC is Equipment cost, BC is bits cost, FLC is fuel cost, EDC is Explosive and drilling cost, and

Yr is the year under review.

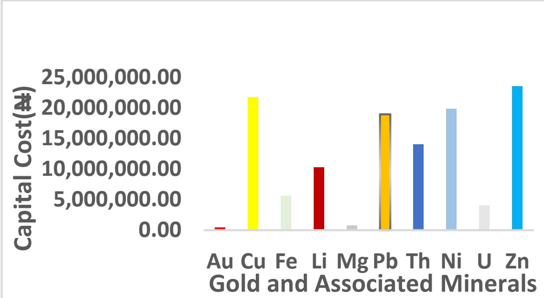

Fig. 5: Modeled Capital Cost Associated with mine parameters Cost Indexes

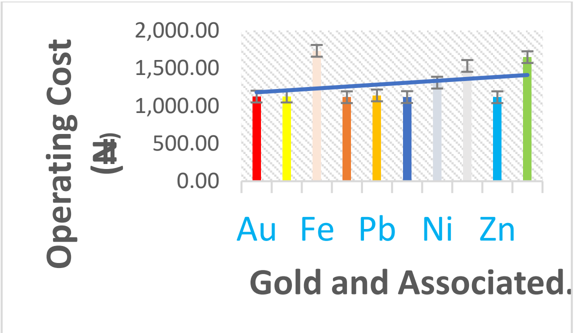

Fig.6: Modeled Operating Cost Associated with Mine Parameters Cost Indexes

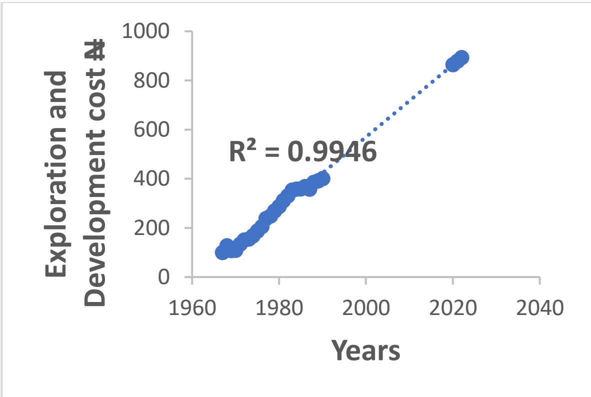

Fig. 7: Exploration and Development Cost Index

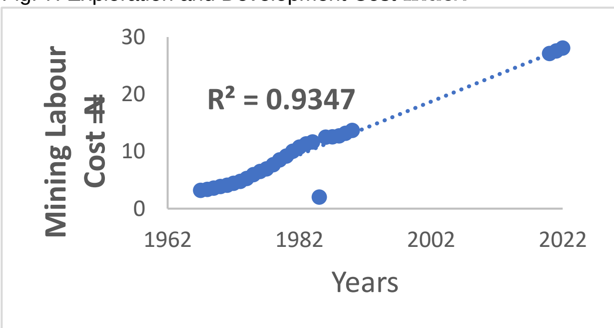

Fig. 8: Mining Labour Cost Index

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4.3 Developed ANN Model Result

The model with a 1:7:10 architecture was built for the gold-associated mineral prediction using ANN Bayesian regularization training algorithms. The respective performances of the ANN training and testing processes are shown in Figure 9. The development process has R^2 =0.703 for the training dataset and R^2 =0.83 for the testing dataset.

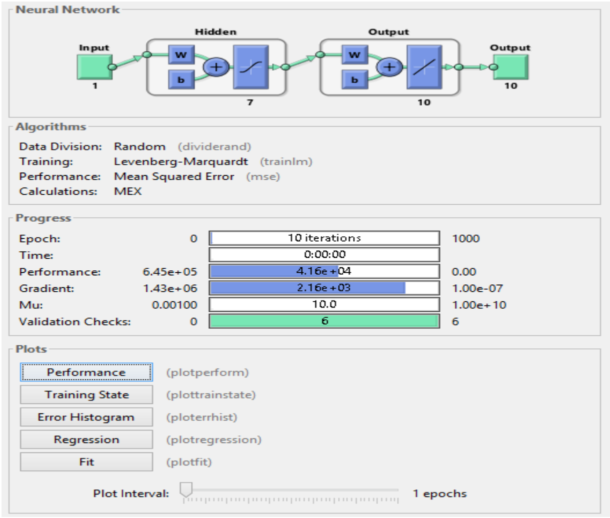

Fig. 9: ANN model training structure and hyper-parameters

The optimum ANN model for all the economic value of the gold associated minerals was extracted into a series of linear mathematical equations after optimum training. The input and output bias and weight of the optimized model were extracted and de-normalized to obtain Equations. (14-23).

ZN = (25.61($\sum_{i=1}^{7} Xi - 0.1677$)+51.68) ×MPT) - (CCT + OCT) (14)

X_1=0.0934tanh (9.56037Au-10.0367)
X_2=0.7566tanh (-9.41179Au+7.0406)
X_3=-0.40301tanh (10.6842Au-0.3151)
X_4=-0.5548tanh (-8.4788Au+0.35857)
X_5=-0.1615tanh (-10.9327Au+1.8731)
X_6=0.0491tanh (-10.9327Au-6.67209)
X_7=0.5802tanh (-8.9377Au-10.9813)

Where ZN is the estimated cost of gold associated Zinc benefit in ₦,
MPT is ₦54,000, the market price of zinc,
CCT is ₦466,226.51, the capital cost of mining,
OCT is ₦50,958.98, the operating cost of mining.
AU is the gold per ton from each sample,
X_i is the sum of all the seven neurons' series output (X_1 - X_7).

U= (0.8375($\sum_{i=1}^{7} Xi - 0.08685$)+5.8625)× MPT) – (CCT + OCT) (15)

X_1=0.54605tanh (9.56037Au-10.0367)
X_2=-0.1702tanh (-9.41179Au+7.0406)
X_3=-0.5623tanh (10.6842Au-0.3151)
X_4=-0.3615tanh (-8.4788Au+0.35857)
X_5=0.2818tanh (-10.9327Au+1.8731)
X_6=-0.3974tanh (-10.9327Au-6.67209)
X_7=-0.20697tanh (-8.9377Au-10.9813)

Where U is the estimated cost of Uranium in ₦,
MPT is ₦25,000, the market price of Uranium,
CCT is ₦466,226.51, the capital cost of mining,
OCT is ₦50,958.98, the operating cost of mining.
AU is the gold per ton from each sample,
X_i is the sum of all the seven neurons' series output (X_1 - X_7).

Th = (21.10($\sum_{i=1}^{7} Xi + 0.51101$)+21.50) MPT) - (CCT + OCT) (16)

X_1=-0.1425tanh (9.56037Au-10.0367)
X_2=-0.7856tanh (-9.41179Au+7.0406)
X_3=0.3356tanh (10.6842Au-0.3151)
X_4=0.4171tanh (-8.4788Au+0.35857)
X_5=0.1217tanh (-10.9327Au+1.8731)
X_6=0.1023tanh (-10.9327Au-6.67209)
X_7=0.2334tanh (-8.9377Au-10.9813)

Where Th is the estimated cost of Thorium in ₦,
MPT is ₦90,000, the market price of Thorium,
CCT is ₦466,226.51, the capital cost of mining,
OCT is ₦50,958.98, the operating cost of mining.
AU is the gold per ton from each sample,
X_i is the sum of all the seven neurons' series output (X_1 - X_7).

Pb= (94.40($\sum_{i=1}^{7} Xi - 0.7069$)+94.6) × MPT) – (CCT+ OCT) (17)

X_1=-0.2142tanh (9.56037Au-10.0367)
X_2=0.0869tanh (-9.41179Au+7.0406)
X_3=-0.0318tanh (10.6842Au-0.3151)
X_4=-0.1136tanh (-8.4788Au+0.35857)
X_5=-0.0484tanh (-10.9327Au+1.8731)
X_6=-0.0211tanh (-10.9327Au-6.67209)
X_7=0.3202tanh (-8.9377Au-10.9813)

Where Pb is the estimated cost of Lead in ₦,
MPT is ₦10,000, the market price of Lead,
CCT is ₦466,226.51, the capital cost of mining,
OCT is ₦50,958.98, the operating cost of mining.
AU is the gold per ton from each sample,
X_i is the sum of all the seven neurons' series output (X_1 - X_7).

Ni= (44.075($\sum_{i=1}^{7} Xi - 0.1739$)+44.325)× MPT) – (CCT + OCT) (18)

X_1=-0.6729tanh (9.56037Au-10.0367)
X_2=-0.3767tanh (-9.41179Au+7.0406)
X_3=-0.0955tanh (10.6842Au-0.3151)
X_4=0.0355tanh (-8.4788Au+0.35857)
X_5=0.09867tanh (-10.9327Au+1.8731)
X_6=0.05518tanh (-10.9327Au-6.67209)
X_7=0.6651tanh (-8.9377Au-10.9813)

Where Ni is the estimated cost of Nickel in ₦,
MPT is ₦10,000, the market price of Nickel,
CCT is ₦466,226.51, the capital cost of mining,
OCT is ₦50,958.98, the operating cost of mining.
AU is the gold per ton from each sample,

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X_i is the sum of all the seven neurons' series output (X_1 - X_7).

$$Mn = (1462(\sum_{i=1}^{7} Xi - 2.1381)+1618) \times MPT) - (CCT + OCT) \quad (19)$$

X_1=0.29195tanh (9.56037Au-10.0367)
X_2=0.1120tanh (-9.41179Au+7.0406)
X_3=0.2354tanh (10.6842Au-0.3151)
X_4=0.4905tanh (-8.4788Au+0.35857)
X_5=0.2401tanh (-10.9327Au+1.8731)
X_6=0.0949tanh (-10.9327Au-6.67209)
X_7=-1.6112tanh (-8.9377Au-10.9813)

Where Mn is the estimated cost of Manganese in ₦,
MPT is ₦5,000, the market price of Manganese,
CCT is ₦466,226.51, the capital cost of mining,
OCT is ₦50,958.98, the operating cost of mining.
AU is the gold per ton from each sample,
X_i is the sum of all the seven neurons' series output (X_1 - X_7).

$$Mg= (0.39(\sum_{i=1}^{7} Xi + 0.7507)+0.42) \times MPT) - (CCT + OCT) \quad (20)$$

X_1=-0.5455tanh (9.56037Au-10.0367)
X_2=-0.5826tanh (-9.41179Au+7.0406)
X_3=-0.7707tanh (10.6842Au-0.3151)
X_4=0.62287tanh (-8.4788Au+0.35857)
X_5=0.1025tanh (-10.9327Au+1.8731)
X_6=-0.6629tanh (-10.9327Au-6.67209)
X_7=-0.05809tanh (-8.9377Au-10.9813)

Where Mg is the estimated cost of Magnesium in ₦,
MPT is ₦10,000, the market price of Magnesium,
CCT is ₦466,226.51, the capital cost of mining,
OCT is ₦50,958.98, the operating cost of mining.
AU is the gold per ton from each sample,
X_i is the sum of all the seven neurons' series output (X_1 - X_7).

$$Li= (14.0 (\sum_{i=1}^{7} Xi - 0.6726)+16.0) \times MPT) - (CCT + OCT) \quad (21)$$

X_1=-0.1474tanh (9.56037Au-10.0367)
X_2=-0.0420tanh (-9.41179Au+7.0406)
X_3=0.2271tanh (10.6842Au-0.3151)
X_4=0.0339tanh (-8.4788Au+0.35857)
X_5=0.3543tanh (-10.9327Au+1.8731)
X_6=0.2716tanh (-10.9327Au-6.67209)
X_7=-0.7672tanh (-8.9377Au-10.9813)

Where Li is the estimated cost of Lithium in ₦,
MPT is ₦6,500, the market price of Lithium,
CCT is ₦466,226.51, the capital cost of mining,
OCT is ₦50,958.98, the operating cost of mining.
AU is the gold per ton from each sample,
X_i is the sum of all the seven neurons' series output (X_1 - X_7).

$$Fe= (7.245 (\sum_{i=1}^{7} Xi - 0.8752)+7.755) \times MPT) - (CCT + OCT) \quad (22)$$

X_1=-0.6283tanh (9.56037Au-10.0367)
X_2=-0.6104tanh (-9.41179Au+7.0406)
X_3=0.2977tanh (10.6842Au-0.3151)
X_4=0.8274tanh (-8.4788Au+0.35857)
X_5=0.5264tanh (-10.9327Au+1.8731)
X_6=-0.2476tanh (-10.9327Au-6.67209)
X_7=-0.0329tanh (-8.9377Au-10.9813)

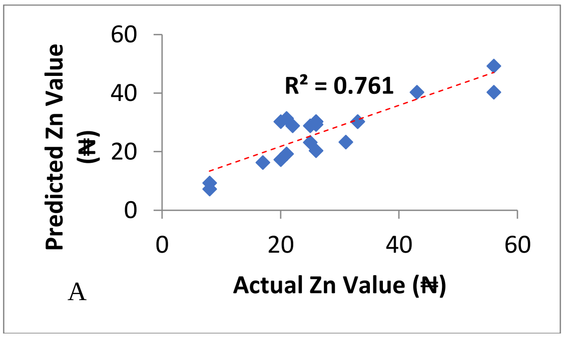
Where Fe is the estimated cost of iron ore in ₦,
MPT is ₦40,000, the market price of Iron,
CCT is ₦466,226.51, the capital cost of mining,
OCT is ₦50,958.98, the operating cost of mining.
AU is the gold per ton from each sample,
X_i is the sum of all the seven neurons' series output (X_1 - X_7).

$$Cu= (53.8 (\sum_{i=1}^{7} Xi - 0.5177)+59.2) \times MPT) - (CCT + OCT) \quad (23)$$

X_1=-0.5550tanh (9.56037Au-10.0367)
X_2=-0.2384tanh (-9.41179Au+7.0406)
X_3=0.1155tanh (10.6842Au-0.3151)
X_4=0.3059tanh (-8.4788Au+0.35857)
X_5=0.1661tanh (-10.9327Au+1.8731)
X_6=0.0883tanh (-10.9327Au-6.67209)
X_7=-0.4679tanh (-8.9377Au-10.9813)

Where Cu is the estimated cost of Copper in ₦,
MPT is ₦180,000, the market price of Copper,
CCT is ₦466,226.51, the capital cost of mining,
OCT is ₦50,958.98, the operating cost of mining.
AU is the gold per ton from each sample,
X_i is the sum of all the seven neurons' series output (X_1 - X_7).

The extracted model was validated with new 20 data set, the predicted results were compared with the economic cost model result as present in Figure 11. The coefficient of correlation of the zinc model (R^2 = 0.761), the uranium model (R^2 = 0.737), thorium (R^2 = 0.865), lead (R^2 = 0.781), nickel (R^2 = 0.839), manganese (R^2 = 0.764), magnesium (R^2 = 0.62), lithium (R^2 = 0.808), iron (R^2 = 0.817), and copper (R^2 = 0.878), respectively. The visualized relationship between the predicted economic worth and the calculated values are presented in Figures 10a – 11j. The results show that the extracted ANN equations are replicates of their respective ANN soft computing models and are suitable for economic estimation of gold's prominent associated minerals.



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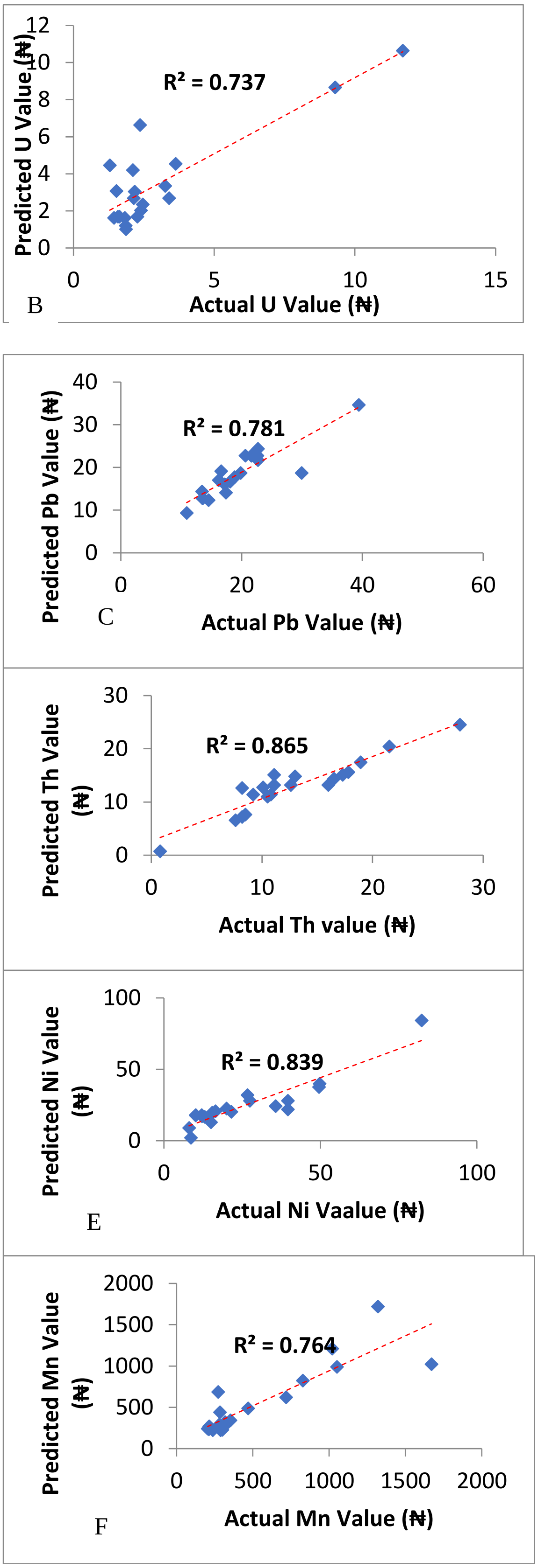

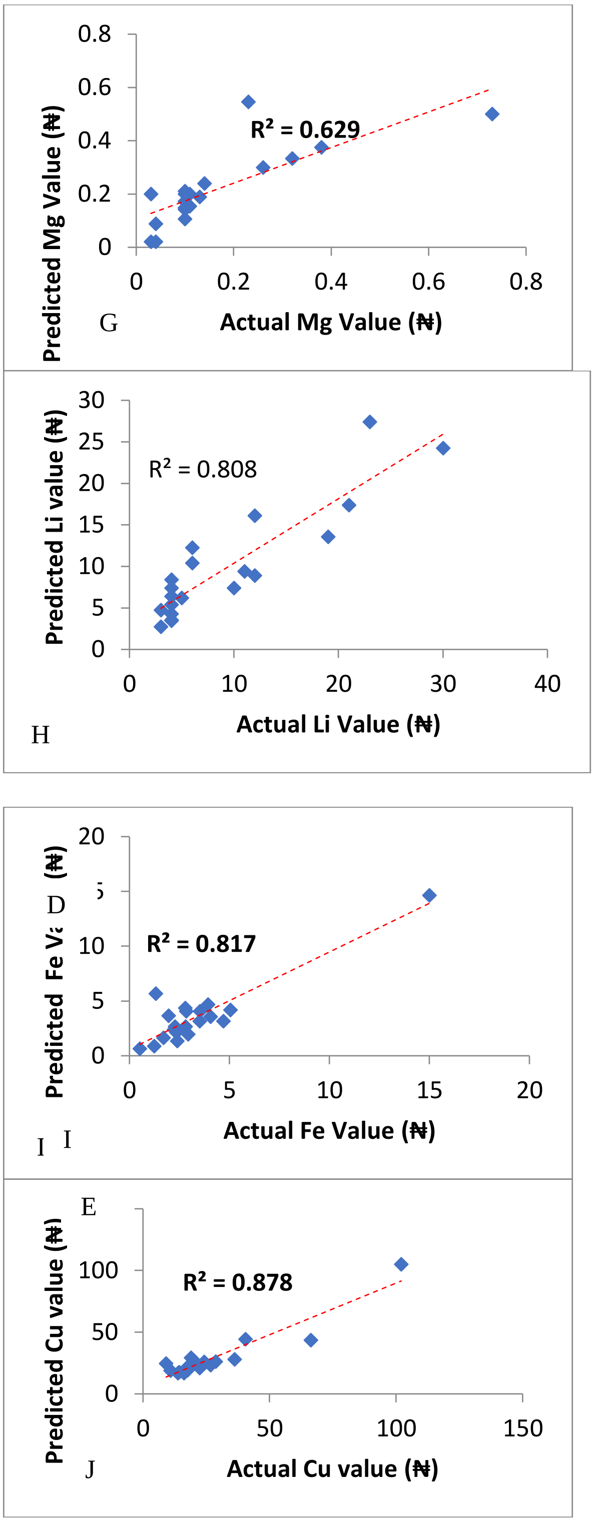

Fig. 10: Relationship between the Actual and Predicted Associate Minerals Economic Value

Figure 11 presents the model validation results for all the ten associate minerals. The model results show that, the extraction of iron, lithium, magnesium, Nickel, lead, and uranium as individual ore will result in capital loss without profit as highlighted in Figure 11. The finding revealed that, combine extraction of both gold and the associate minerals improve mining profit margin and account for both operation and capital cost.

4.4. Model Validation Results

Validation results of the models were carried out using coefficient of correlation (R^2), Root means square error (RSME), and Variance account for (VAF). Figure 12 present the validation results of the 10 models using

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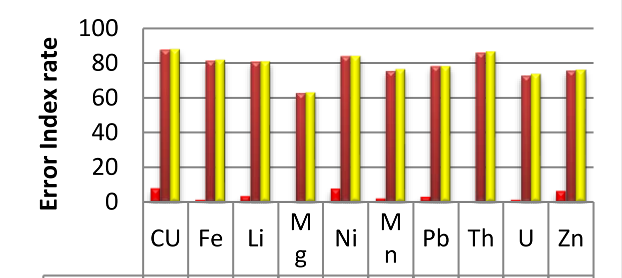
coefficient of correlation (R^2), Root means square error (RSME), and Variance account for (VAF). In terms of R^2 and VAF, the model shows high correlation with low variance between the predicted and the measured quantity of all the associate minerals. According to the root mean square error values, the low results revealed that the predicted values of the associated minerals are closer to the measured values. As a result, the developed model prediction performance is appropriate for the estimation of gold associate mineral economic benefits.



	CU	Fe	Li	Mg	Ni	Mn	Pb	Th	U	Zn
RSME	7.6	1.3	3.4	0.1	7.5	2.1	3.0	0	1.4	6.1
VAF	88	81	81	63	84	76	78.	86	73	76
R2	88	82	81	63	84	76	78.	87	74	76

Fig. 11: cost-based model Validation Graph

5. Conclusion

The study was carried out to develop cost-based model for gold and associated mineral in Birnin Gwari and Kagara gold deposit in Nigeria. The following findings and conclusions were drawn from the study;

1. The location survey indicated that the gold specks in the case study area occur within the quartzite and schist veins. The identified veins length ranges from less than 50 m to 600 m, while the width ranges from a few 5 m to 20 m. The depth to the top of the vein ranges between 5 m and 70 m. The identified veins were plotted on their mineral prospective maps for both the Birnin Gwari and Kagara formations. The geochemical analysis results revealed that the maximum and minimum values of gold concentrate recovered ranged from 0.22 g/t for some sample points.

2. The total gold concentration in the Birni Gwari study area was 4.87 g/t, while the total gold concentration in the Kagara study area was 2.92 g/t. In general, 52% of the gold veins in the Birnin Gwari formation were found to occur in pegmatite or schist, while alluvial holds 48% of the gold. However, in the Kagara study area, pegmatite or schist holds about 33% of gold, while alluvial holds 67% of gold.

3. The questionnaire survey results indicate that the estimated value of gold mined daily is N 876,600 and N 412,200 in Birni Gwari and Kagara, respectively.

4. Cost based models were also developed using artificial neural network approach to predict the economic cost-benefit of gold-associated minerals in gold formations. In terms of R^2 and VAF, the model shows a high correlation with low variance between the predicted and measured quantities of all the associate minerals. According to the root mean square error (RMSE) values, the low results revealed that the predicted values of the associated minerals are closer to the measured values. As a result, the developed model's prediction performance is appropriate for the estimation of gold-associated mineral economic benefits.

5. Recommendations

Based on the outcome of this study, the following recommendations are offered;

With the current economic diversification agenda of the present administration to solid minerals development, government should come to the aid of artisanal miners and investors financially to enable them make use of three key exploration methods (Geophysical, Geological and Geochemical) before embarking on mining activities for effective delineation and maximum exploitation of mineralized zones. This will reduce cost of mines development and increase the profit margin.

Results from the study areas indicates a low gold, mineralized zone, therefore, effort to win gold and other associated minerals should be directed to both alluvia and pegmatite rocks. This is to increase the rate of production and to guide against closure of mines abruptly.

iii. The study areas are full of more associated minerals with gold. Government in partnership with independent private investors can finance the project with modern mining equipment, human and material resources within and from abroad to open up the study areas so as to make the study areas be the hub of mining destination.

iv. The cost-based model developed from this study is recommended for all mining operators and investors engaging open pit mining operations. This will help forecast the feasibility of the mines, the type of equipment to be used, the mining labour and technology to use for optimum cash flows.

v. The model developed is pertinent as a guide for both the potential investors into gold mining sector and the Federal Government of Nigeria on her economic diversification agenda.

vi. The model's ambit developed is also recommended for use as it guides against operating a single unit mineral to avoid loss profit margin.

Availability of Data and Materials

The data used in the study were the laboratory analysis results from intensive geological, geophysical and geochemical surveys caried out at the study areas

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All sections of the manuscript including data collection, analysis and interpretation were carried out by the author.

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