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Regular Research Manuscript

A Fuzzy Based Framework for Sustainable Technology Selection in Small-Scale Gold Mining Operations

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ABSTRACT

Small-scale gold mining (SSGM) operations in Tanzania has been operating inefficiently due to inadequate mining processing technologies, poor working tools, lack of enough capital, and insufficient electricity. Despite the efforts made by different stakeholders in boosting the sustainability of SSGM yet the sector has not reached the expected goal. This paper proposes a framework for appropriate technology selection to help small scale gold miners in evaluating various gold mineral processing technologies. The framework utilizes the fuzzy logic set theory for technology evaluation and selection. The developed framework for technology selection upon validation provided results that technology adequacy of more than 60% and the economic value of above 80% has low environment effect of about 16%. Similarly, obsolete technology of 45 years has a disposal effect of 5% on the environment. The study concluded that semi-mechanised crushing and grinding, gold concentration shaking table, square-set timber and stull stopping mining technologies for the shaft underground mining and cyanide chemical leaching are sustainable technologies in SSGM operation in Tanzania. The study recommended the adoption of technology selection framework developed and practised prior mining project commencement for sustainable SSGM in Tanzania.

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INTRODUCTION

Gold mining activities in Tanzania have passed through various stages of economic reforms as a result of Government leadership and policy changes. Historical data shows that gold production was at the peak after the gold discovery and exploitation by German colonialists in the 19th Century when it contributed to about 90% of the value of the mineral revenues, and during the British colonial era (1918 - 1961), when the contribution of mining to GDP averaged 3% - 4% (Lange, 2006). However, studies reveal that mining industry experienced several problems that caused by low income due to low production, low skills level, poor equipment and technology, poor infrastructure, lack of sustainable electricity and unfavourable political environment, (Chusi, 2024).

After independence in 1961, the natural resources were under State Mining Corporation (STAMICO) and the National Development Corporation (NDC). During this period, artisanal and small scale miners (ASM) rose production of gold from 150,000 in 1987 to over 700,000 in 2011, and it increased to 1.5 million tonnes/kg by June, 2018 (Mutagwaba *et al*., 2018).

However, in the second half of the 1980s Tanzania made huge economic reforms and therefore, policies were reviewed to incorporate privatization and liberalization. The review of policies made the then Ministry of Energy and Minerals come up with *the Mineral Policy of 1997* and in 2009, another mineral policy (i.e., *Mineral Policy of 2009*) was formed following an evaluation done on the implementation of the Mineral Policy of 1997. All mineral policies are focused on strengthening attraction of investors and maximizing benefits from the mining industry for sustainable development. The average contribution of the mining sector in Tanzania's economic growth gradually increased from 0.2% to 3.4% in 1999 - 2008 respectively (Mdee, 2015).

It was expected that following the review of policies and Acts, small-scale gold mining (SSGM) productivity and performance would increase sustainably as a result of the increased small-scale gold mining operations. Instead, gold productivity and the environment have been impacted by the current applied mineral processing technologies as shown by numerous studies such as Iglesias-Martínez *et al*., (2024)

Therefore, this paper proposes a framework to be adopted in evaluating and selection appropriate technology to be applicable in SSGM. The framework will help decision makers step-by-step in selecting and evaluating the technology during operations in SSGM.

Criteria and Characteristics of Small-Scale Mining (SSM)

The common criteria of SSM in different countries are defined mostly based on investment costs, ore production rate, labour skills requirements, size of mine claims, ore reserves, sales volume, operational continuity, operational reliability and any other standard related to SSM activities as shown in Table 1. This paper defines small-scale gold miners in the context of operations, working tools and investment capital of less than USD 100,000 with mining claim of not more than 10 hectares.

The Concept of Sustainability

The sustainability concept in mining operation emerged after showing that mining operations are an agent of environmental pollution which differs widely depending on the nature of pollutant being produced during the mining operations. The mining operations as a source of wealth flow has also socio-economic impacts as they affect workers, their families, the community surrounding the mining sites, and the country in general (Chanthy, 2021). Considering minerals are non-renewable natural resources, the world is looking at the mining operations that has no or minimum adverse effects on environment, society, and economy. The mining activities has to be performed without affecting the ecosystem while meeting today's development and future needs after the mine closure (Ampaw et al., 2024).

Therefore, in the context of this study sustainability in SSGM operations are mining and processing operations practices that serve the sustainability of environment, economic and social aspects as shown in Figure 1.

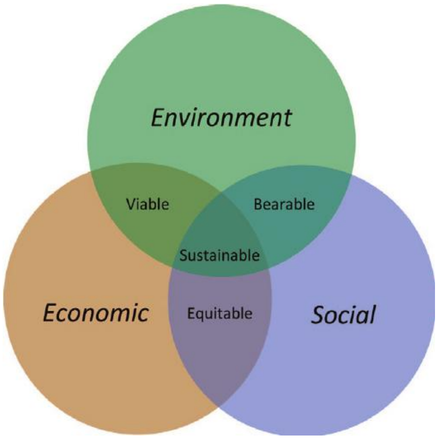


Figure 1: The pillars of sustainability in mining industry (Bansal et al., 2024)

Framework for Selection of Mining Technology

The use of a framework in decision-making aids in identifying and categorizing the processes or steps involved in a complex task or thought process, making implicit and tacit elements more explicit. According to Liu et al (2024) and (Kafuku et al., 2016) framework refers to a basic structure to show a flow of process that should be conducted advantageously and sustainably. The framework outlines important steps for selecting technology for the performance of small-scale gold mining.

Technology Selection

Technology, in general, is the collection of techniques, knowledge, skills, tools, methods, systems, processes and human integration used in the production of goods or services or the accomplishment of the desired goal.

Technology selection process is complex because technology is embedded in all pillars of sustainability. According to Tanveer *et al.*, (2023) and Araujo et al (2023), the justification for the selection of technology in such complex situation considers multiple criteria and options for decision making which include the analysis of the economic, environment, social, strategy, reliability, ease of adoption and principal inputs such as proximity to raw materials and manpower availability are criteria to meet the requirements of sustainability. Table 2 shows the common techniques used for the technology selection decision making justification.

The analytic assessment of technology has been considered in this paper as the absolute approach of selecting technology because of its advantage of taking into account of several priorities of decision-making criteria. Different multi-criteria decision making (MCDM) methodologies for the selection of technology has been developed by different researchers. For instance, Borrás et al (2024)developed an improved MCDM DEA model for technology selection in the presence of ordinal data; Yahya *et al* (2024) developed an integrated fuzzy approach for the selection of manufacturing technologies; Naghadehi, Mikaeil and Ataei (2009) developed a fuzzy analytic hierarchy process (FAHP) approach to selection of optimum underground mining method for Jajarm Bauxite Mine in Iran. Kreng, Wu and Wang (2011) developed an extended analytic hierarchy process (AHP) model for the strategic justification of advanced manufacturing technology selection. Tanveer *et al* (2023) developed a model for selecting technologies in new product development which has reflected the interrelationship of the criteria in the decision making process by combining interpretive structural modeling (ISM) and fuzzy analytic network process (FANP); (Naghadehi et al 2009) developed an integrated fuzzy AHP method for the selection and evaluation of technologies; and Kafuku *et al* (2016) developed fuzzy logic tool for selection of remanufacturing technology.

Table 1: SSGM Common Criteria and Characteristics

S/N	Common Criteria	Characteristics	Other Experience and References
1	Ownership	Licenced or not licenced nationals	Tanzania Mining Act, 2010 (URT, 2010) and the Minerals and Mining Act, 2006 of Ghana (Ghana, 2006)
2	Capital Investment	USD 0 – ≤100,000 or its equivalent to Tanzanian shillings,	URT (2010); R8 million in South Africa and USD 1 million in Thailand (Opoku-Antwi, 2012).
3	Degree of Mechanisation	Manual work to a lot of activities due to lack of or limited use of mechanization such as the use of sledgehammers, chisels, local grind mills, and small compressors	Ghana, Tanzania, Burkina Faso, Mali, and Togo categorise by using simple tools and equipment. While in the USA, Russia, and Australia mechanised mining is being used by small-scale miners (Opoku-Antwi, 2012).
4	Depth of Workings	Narrow underground sink shaft up to 150 meters deep	Developing countries like Tanzania have limited mine depth to describe small-scale mining (Labour, 2003).
5	Nature of Working	Seasonal mining operations. Most mine operations are stopped due to lack of pumps to pump out water	Ghana, Tanzania, Burkina Faso and Togo where nature of working for most miners is seasonal (Opoku-Antwi, 2012)
6	Employment	Only unskilled labour to the most level of the mining operations and 1 - 4 semi-skilled (chemist, boilermaker, driver)	Such as Pakistan and United States in underground mines and surface mines in India are considered to be small-scale mines (Labour, 2003).
7	Size of the Claim	For licenced possessing ≤ 2 hectare	Ghana, Zambia, and Zimbabwe (Labour, 2003).
8	Ore Production Capacity	Not more than 200 tonnes of ore produced annually for an individual	Annual output of tonnes of ore processed of about 250,000 tonnes or less regardless of level of mechanisation, type of mine, and the mineral (Labour, 2003).

Source: Researcher's Document Review (2021)

Table 2: Common Techniques for Technology Selection Decision Making

Criterion	Technique for Analysis	Advantage	Disadvantage	References
Economic	Payback Period Method	Ease of data collection	Does not take into account strategic and non-economic benefits.	Araujo et al (2023); Houseman et al (2004),
	Benefit-Cost Analysis			
	Return on Investment	Intuitive appeal		Beemsterboer and Kemp (2016)
	Discounted Cash Flow Methods (NPV, IRR)		Considers only cash flows, and ignores non-monetary benefits	

Environment and Social	Environment and Social Impact Assessment (ESIA)	Considers the likely consequences for the biogeochemical environment and social (man's health and welfare)	Difficulties in data collection and analysis, prediction of effects and assessment of risks in the exercise of EIA	Araujo et al (2023); Houseman et al (2004), Dreschler (2001)
	Environmental Audit (EA)			
Strategic	Technical Importance	Requires less technical data.	The necessity to use these techniques with economic or analytic ones since they consider only long-term intangible benefits	Araujo et al (2023); Houseman et al (2004), Saaty (2008)
	Business Objectives			
	SWOT (Competitive Advantage)	Considers general internal and external objectives of the firm environment.		
	Research and Development			
Analytic	Multi-criteria Scoring Models Hierarchy Process (AHP)	The multi-decision analysis incorporated tangible, intangible and future uncertainties	More data is required for all set of priorities.	Araujo et al (2023); Houseman et al (2004), (Naghadehi et al., 2009)
	-Data Envelopment Analysis (DEA)	Captures both subjective and objective aspects of a decision.	Complexity in economic analysis as it considers monetary and non-monetary	Borrás, Ruiz and Sirvent, (2024) Kafuku *et al*. (2016)
	Fuzzy Set Theory			

Source: Researcher's Document Review (2020)

Figure 2: Modified and Adopted Hierarchical Framework for Technology Selection

Source: Kafuku *et al*. (2016)

The major constrained of the models is that the majority does not consider parameters/factors to leverage complexity of technology in small scale gold mining industry. This paper adopted a holistic framework developed by Kafuku *et al* (2016) for selection of remanufacturing technology using Fuzzy logic tool.

The framework considered lifecycle of technology with three operations phases as shown in Figure 2. The phases are technology identification and selection phase, technology acquisition and use phase, and technology obsolete and disposal.

METHODOLOGY

The data was collected by interview, questionnaire, document review, and expert opinion. The method applied for data analysis was the Fuzzy Set Theory and fuzzy logic tool in MatLab software. The outputs of data analysis were presented in the form of figures and text for easy interpreting the results. The research methodology was governed by the flow of procedures shown in Figure 3. Description of each step of a fuzzy based framework are as follows:

Step 1: Identification of current technologies in SSGM

Criteria used for identification of technology are production capacity, customer demand, gold quality, rival pressures, regulatory compliance needs, cost serving, and raw materials availability.

Step 2: Develop criteria for technology selection

The step is about developing qualitative and quantitative measures to help expert to make decision making. For this paper, the criteria were scrutinized and adjusted to make sure that the priorities are minimal, non-redundant, measurable, and comprehensive to achieve technology selection.

Step 3: Evaluation of technologies

The steps in evaluating technologies consider experts opinion during the process of analyzing the linguistic terms converted to fuzzy weights by using the appropriate fuzzy membership functions designed based on Likert scale.

Step 4: Experts Judgement using fuzzy set theory

Step 4.1: Creating a Pairwise Comparison Matrix **A**

The pairwise comparison matrix **A** considering procedures and conditions as follows:

- Matrix **A** should be $m \times m$ real matrix, where m is number of assessment priorities among the criteria considered.
- Each entry a_{jk} of the matrix **A** represents the importance 1 of the j^{th} criterion relative to the k^{th} criterion.
- If $a_{jk} > 1$, then the j^{th} criterion is more important than the kth criterion.
- Whereas, if $a_{jk} < 1$, then the j^{th} criterion is less important than the kth criterion.
- If the two criteria have equal importance, then the entry a_{jk} is 1.

$$A=\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \quad (1)$$

If decision-makers believe that technology performance concerning quality is 1, then it means there is a very high chance of adopting quality mining technology.

Step 4.2: Normalization of the Pairwise Comparison Matrix **A** *norm*

A normalized pairwise comparison matrix **A** *norm* is then derived from the created matrix A. That is, the sum of all elements on each column of the matrix A should be equal to 1. Each element entry $\bar{a}$jk of the matrix **A** *norm* is calculated as follows:

$$\bar{a} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}} \quad (2)$$

Step 4.3: Computation of the Vector of the Criteria Weights

Lastly, after obtaining the normalized matrix, the *criteria weight vector* **w** (that is an *m*-dimensional column vector) is established by computing the average of the element entries on each row of the normalized matrix **A** *norm* as follows:

$$\boldsymbol{w}_j = \frac{\sum_{l=1}^{m} \bar{\boldsymbol{a}}_{jl}}{m} \qquad (3)$$

Step 4.4: Computing the Matrix of Alternative Scores S

Similarly; at this stage, the pairwise comparison matrices of the alternatives are also created and should be in the form of *n x m* real matrix **S** with entry elements $\mathbf{S}_{ij}$ where i^{th} represents the alternative corresponding to the j^{th} criterion. The sub-steps below describe the procedures for the creation of the matrix of each alternative score **S.**

Step 4.5: Creation of a Pairwise Comparison Matrix $\mathbf{B}^{(j)}$

For each criterion *m* with *j = 1,…, m*. the $\mathbf{B}^{(j)}$, the matrix should follow *n x n* real matrix condition, where *n* stands for the alternatives available to be assessed. For each element, entry $\boldsymbol{b}_{ih}^{(j)}$ refers to the evaluation of the i^{th} alternative compared to the h^{th} alternative about the j^{th} criterion. According to (Fernandes & Palma, 2024) , the condition for comparison and thereafter the selection is that if $\boldsymbol{b}_{ih}^{(j)}>1$ means the i^{th} alternative is better than the h^{th} alternative, whilst if $\mathbf{b}_{ih}^{(j)} <1$ means the i^{th} alternative is not as good as the h^{th} alternative. If the two alternatives evaluated are equivalent about the j^{th} criterion, then the entry $\mathbf{b}_{ih}^{(j)}$ is 1 and thus the entries $\boldsymbol{b}_{ih}^{(j)}$ and $\boldsymbol{b}_{hi}^{(j)}$ must satisfy the following condition:

$$\boldsymbol{b}_{ih}^{(j)} \cdot \boldsymbol{b}_{hi}^{(j)} = 1 \qquad (4)$$

Likewise, $\boldsymbol{b}_{ii}^{(j)} = 1$ for all given *i.* Again, the fundamental evaluation scale nine-point for AHP table 2.7 above can be used in the translation of pairwise evaluations into numbers.

Step 4.6: Normalization of the Pairwise Comparison Matrix $\mathbf{B}^{(j)}$*norm*

A normalized pairwise comparison matrix $\mathbf{B}^{(j)}$*norm* is then derived from the created matrix $\mathbf{B}^{(j)}$. that is, the sum of all elements on each column of the matrix $\mathbf{B}^{(j)}$should be equal to 1. Each element entry $\overline{\boldsymbol{b}_{ih}^{(J)}}$ of the matrix $\mathbf{B}^{(j)}$*norm* is calculated by dividing each element entry by the total sum of all the elements in the same column:

$$\overline{\boldsymbol{b}_{ih}^{(J)}} = \frac{\boldsymbol{b}_{ih\ jh}^{(j)}}{\sum_{l=1}^{n} \boldsymbol{b}_{ih\ lh}^{(j)}} \qquad (5)$$

where *j* = 1,…, *m*

Step 4.7: Computation of the Vectors of the Alternative Weights **S**

Lastly, after obtaining the normalized alternative matrix, the alternative weight vectors $\boldsymbol{s}^{(j)}$ (that is an *n*-dimensional column vector for j^{th} criterion *j=1,...,m*) is established by computing the average of the elements entries on each row of the normalized matrix $\mathbf{B}^{(j)}$*norm* as follows:

$$\boldsymbol{s}^{(j)} = \frac{\sum_{l=1}^{n} \overline{\boldsymbol{b}_{ih}^{(J)}}}{n}$$

again *j* = 1,…, *m* (6)

Hence, the alternative weight score matrix **S** for a given *j=1,…,m* is established as:

S = [s(*j*) ... ***s***(*m*)] (7)

That is, the j^{th} column of **S** corresponds to $\boldsymbol{s}^{(j)}$

Step 4.8: Ranking of technology alternatives based on the crisp scores

The obtained overall crisp scores are used to rank each alternative technology evaluated whereby the technology with the highest overall score is selected and adopted. Ranking of the alternatives is done by first obtaining the vector $\boldsymbol{v}$ of the total scores by multiplying the alternative weight score matrix **S** and the criteria weight vector $\boldsymbol{w}$:

$$\boldsymbol{v} = \mathbf{S} \cdot \boldsymbol{w} \quad (8)$$

Then, the obtained global score vector V is now used for ranking the alternative evaluated whereas the i^{th} entry is the $\boldsymbol{v}_i$ of the global score vector $\boldsymbol{v}$ representing the final total score assigned to the ith alternative. Thereafter, the ranking is done by arranging the alternative total scores in decreasing order.

Step 5:Checking the Consistency

According to Fernandes and Palma, (2024), a pairwise comparison matrix to be built should satisfy the consistency ratio (CR) of less than 10%. Whenever the condition is not fulfilled, it means there is an inconsistent and modification of the pairwise comparison matrix must be done to obtain CR score which is less than 10%. The technique incorporated in AHP for checking the consistency depends on the computation of a Consistency Index (CI) and is given by:

The first step is the calculation of the scalar $\boldsymbol{x}$ which is obtained by computing the scalar x as the average of the elements of the vector whose jth element is the ratio of the jth element of the vector $\mathbf{A}\cdot\boldsymbol{w}$ to the corresponding element of the vector $\boldsymbol{w}$.

$$CI = \frac{x-m}{m-1} \quad (9)$$

where m is the number of evaluation criteria considered in the process of computing the vector of criteria weights. Similarly, when computing the CI for the pairwise matrices for the alternative weights, instead of $\boldsymbol{m}$, the number of evaluation alternatives $\boldsymbol{n}$ is considered in the calculation.
Also, the consistent ratio is given by:

$$CR = \frac{CI}{RI} < 0.1 \quad (10)$$

Where RI is the Random Index, i.e. the consistency index when the entries of a pairwise comparison matrix are completely random. For randomly generated consistency index (RI.), values are given in Table 3 Table. Table 3 presents the values of RI for a small number of iterations (i.e.).

Table 3: Values of Random Index (RI) for Number of Entries ≤ 10

m	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Step 6: *Technology selection*
Selection of the technology through Select the most suitable technology based on the defuzzied results and establishing framework as guiding tool.

Step 7: *Framework validation*

The framework was validated through conducting sensitivity analysis by increasing the weight of different criteria's i.e. cost criteria and observing if the selected technology remains the same.

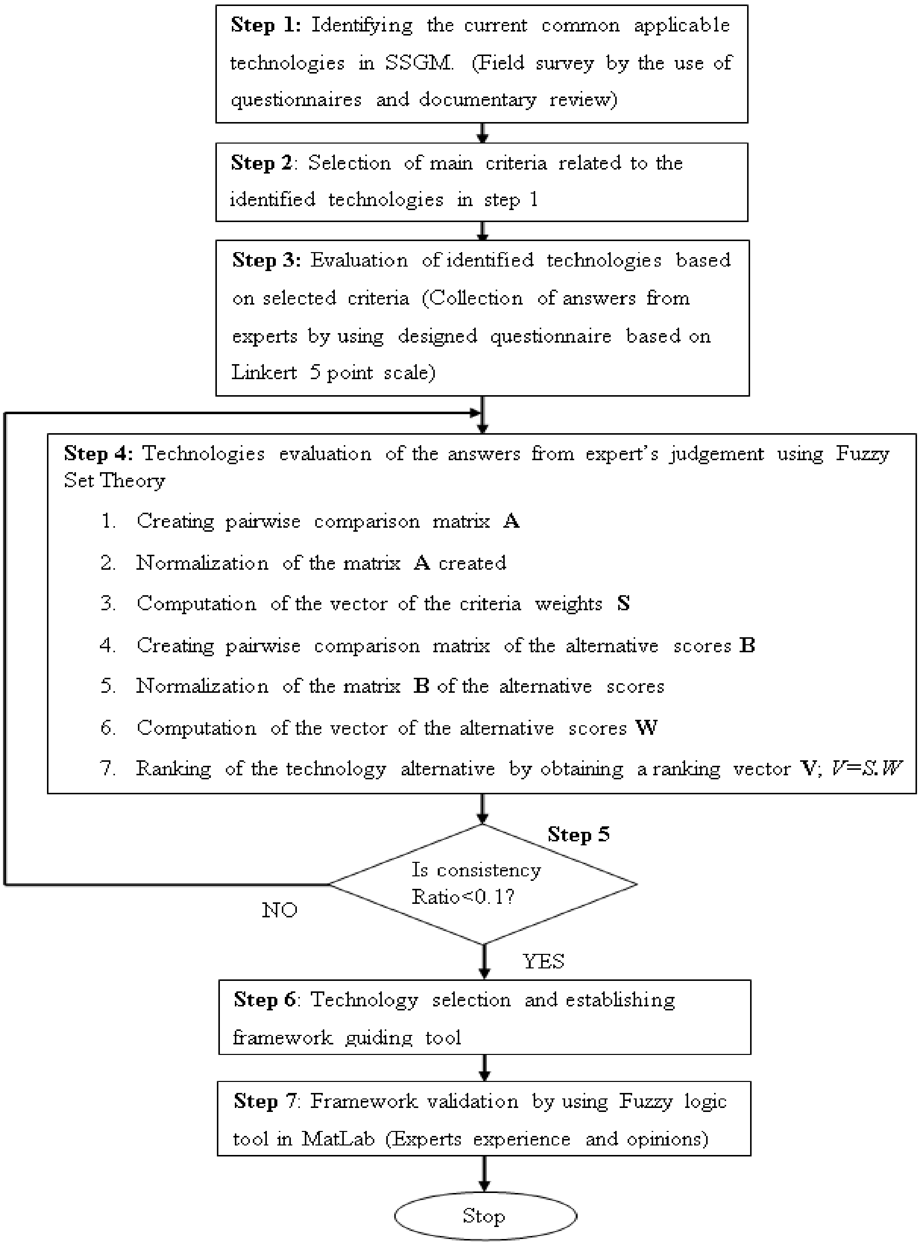


Figure 3: Methodological flow of procedures for data collection and evaluation Source: Adopted and Modified from Kafuku *et al*. (2016)

RESULTS

Applicable Technology in SSGM

Figure 4 shows the findings that the underground (shaft) mining method is commonly techniques used by 83% of SSM. The remaining 17% of SSM uses surface mining at start-up of mining projects before migrating to shaft mining technology when the depth of the ore deposit increase and grade distribution found to be not uniform. Placer mining is not conducted in the case study area because mineral deposit which can be mined by using placer mining technology does not exist. The findings indicate the four applicable technologies for ore size reduction as shown in Figure 4. Figure 5 indicates the applicability of current ore comminution technologies is 100% as the use of non-mechanized (Manual) technologies for crushing ore is common practice. However, 36% use semi-mechanised crusher for crushing ore while technology for grinding crushed ore is used by all plants.

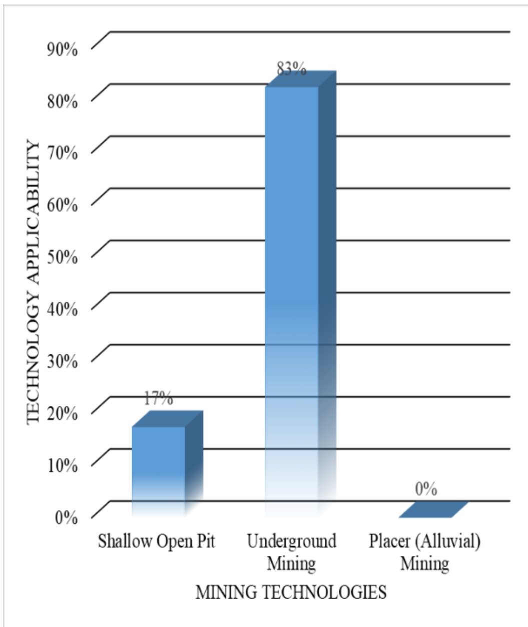


Figure 4: Current applicable mining technologies

Technologies Applied in Ore Comminution Section

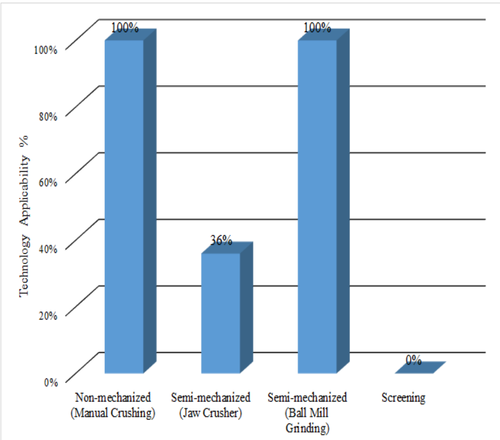


Figure 5: Applicable ore comminution technologies

Existing Gold Concentration Technologies in SSGM

Figure 6 shows that 100% of surveyed plants use non-mechanised technology for sluicing and panning for concentrating milled gold ore. The technology is widely used because of low equipment fabrication and operation costs, availability of materials for fabricating the equipment close to the mine site and it can be operated by any personnel with unskilled, semi-skilled and skilled labours. Figure 7 reveals that 100% of the mine sites use mercury amalgamation, cyanidation static-vat leaching, and smelting chemical processing technologies to recover gold from either primary ore or tailings from gravity circuit. These processing technologies were being used sequentially for the aim of increasing gold recovery.

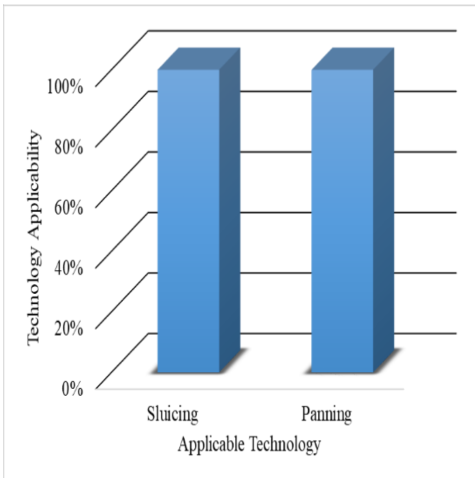


Figure 6: Applicable gravity concentration technologies

Application of Chemical Processing Technologies

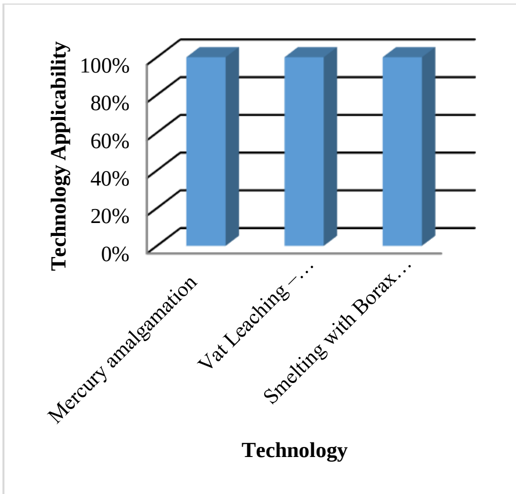


Figure 7: Applicable chemical processing technologies

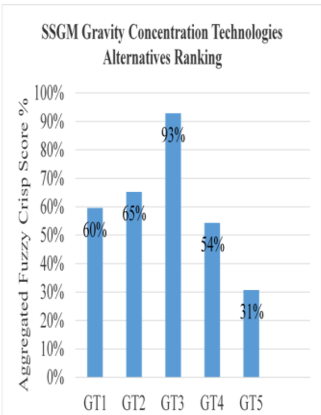
Evaluation of Mining Technologies Alternatives

The alternatives mining and processing technologies were evaluated based on the flow of procedures of the methodology.

The gravity concentration technologies have been considered during evaluation. The sluicing, panning, shaking table, spiral-vortex concentrator, and centrifuges were identified as gravity concentration technologies. The criteria used to evaluate technologies are:

1. Ore physical Criteria: feed particle size, particle density strength and bed mass
2. Economic Criteria: Capital investment cost, operating cost and productivity (Recovery)
3. Environment Criteria: technology obsolete, technology disposal and wastes dumps.
4. Technological Criteria: technology sophistication, energy consumption and water consumption

The criteria were given weighted score based on weight scale of the membership values. After the aggregation of the fuzzy membership, the gravity technology was ranked as per the crisp score presented in Figure 8.



Gravity Technology Options	Tech. ID.
Sluicing	GT1
Panning	GT2
Shaking Table	GT3
Spiral-Vortex concentrator	GT4
Centrifuges Technology	GT5

Figure 8: SSGM Gravity Technologies Alternatives Ranking

The result revealed that shaking table (GT3) technology is appropriate for sustainable SSGM. The technology is suitable for 93% compared to other evaluated options of gravity ore concentration.

Technology for Underground Mining Circle

Shaft-tunnel underground mining circle of operations was established. Combined square-set timber and stull stopping mining technologies proposed for sustainable SSGM operating using shaft and tunnel underground mining.

Technology for Gravity Circuit Circle

Gravity circuit circle was established to be the second circle of operations. The circle comprised of Ore comminution and gold ore concentration circuits.

Semi-mechanised technology for ore size reduction is proposed whereas after technologies evaluation, shaking (Gemini) table technology is proposed for a gravity gold ore concentration circuit to achieve sustainability in SSGM. This technology is proposed because of availability, flexibility, affordable as investing, and operating cost is relatively cheap as can locally been fabricated. Also, the technology requires semi-skilled labour to operate, unskilled labour for loading ore into the equipment and technical personnel to take maintenance and hence manpower availability is assured within the community surrounding the mining areas.

Technology for Gold Ore Chemical Processing Circle

Cyanidation vat leaching and elution chemical processing technology were proposed. These technologies were selected after the discussion of the findings aiming at gold recovery from ore and the conservation of the environment. Today the world is more concern with mining activities that are friendly to environment conservation (Bansal et al., 2024).

Waste and Safety Management Circle

Waste and safety management circle technology were selected to control the effluent from the use of mining and processing technologies. Waste and safety management is a continuous process for the entire life of technologies once being implemented. To bring sustainability in SSGM, waste rocks dump, tailings storage facilities and waste process water management, workforce management and community health monitoring are recommended.

Fuzzy Based Framework for Selection of Sustainable Technology in SSGM Operations

The mode of operations in SSGM was studied to understand the current flow of operations. The field survey revealed that SSGM operations are conducted in two modalities of operations. This mode of operations differs from one miner to another because the scope and targets of small-scale gold miners are different. Factors such as lack of enough investment capital, lack of experienced personnel to operate the equipment, high operating and maintenance cost have been the reasons for miners to conduct their mining operations to either invest and operates all the activities within their mine site or portion of the activities are being conducted in a leased technology (Zheng et al., 2024).
Based on results the proposed fuzzy based framework for selecting technology is shown in Figure 9. The framework shows chosen criteria for economic, environment and technological factors that were considered as pre-requisite factors for sustainable SSGM operations.

Validation of Fuzzy Based Framework

The proposed fuzzy based framework was validated by considering typical minimum life of mine for small scale mining project between 10 years and not more than 50 years (Yahya et al., 2024). The gold ore processing technology was selected for validation because 75% of most of the core activities to recover gold from its ore are entirely done in the processing phase. The validation was done by experts in two mines namely Mara Mine Development Limited (MMDL) and Nyamako Co. Ltd in Nyamongo ward whereas jaw crusher technology was considered.
The validation considered both intrinsic and extrinsic criteria to suffice economic, environmental and social pillars of sustainability. The expert considered eight inputs variables as shown in Table 4.
The variables were analysed by a fuzzy logic tool in MATLAB and the rating conducted based on linguistic point value as *very low*, *low*, *medium*, *good*, and *very good*. The results of technology assessment are presented in Figures 10 – 12.
Figure 10 (a) shows that the technology mechanisation, quality and reliability were used to validate technology adequacy and the indicate that when the level of mechanisation is 90.7%, technology quality of 91.5%, and reliability of 90.7% then technology adequacy was 75.3%. Figure 10(b) shows that when technology mechanism is 12%; technology quality of 12.1%; and technology reliability of 12% results in technology adequacy of 32.8%.

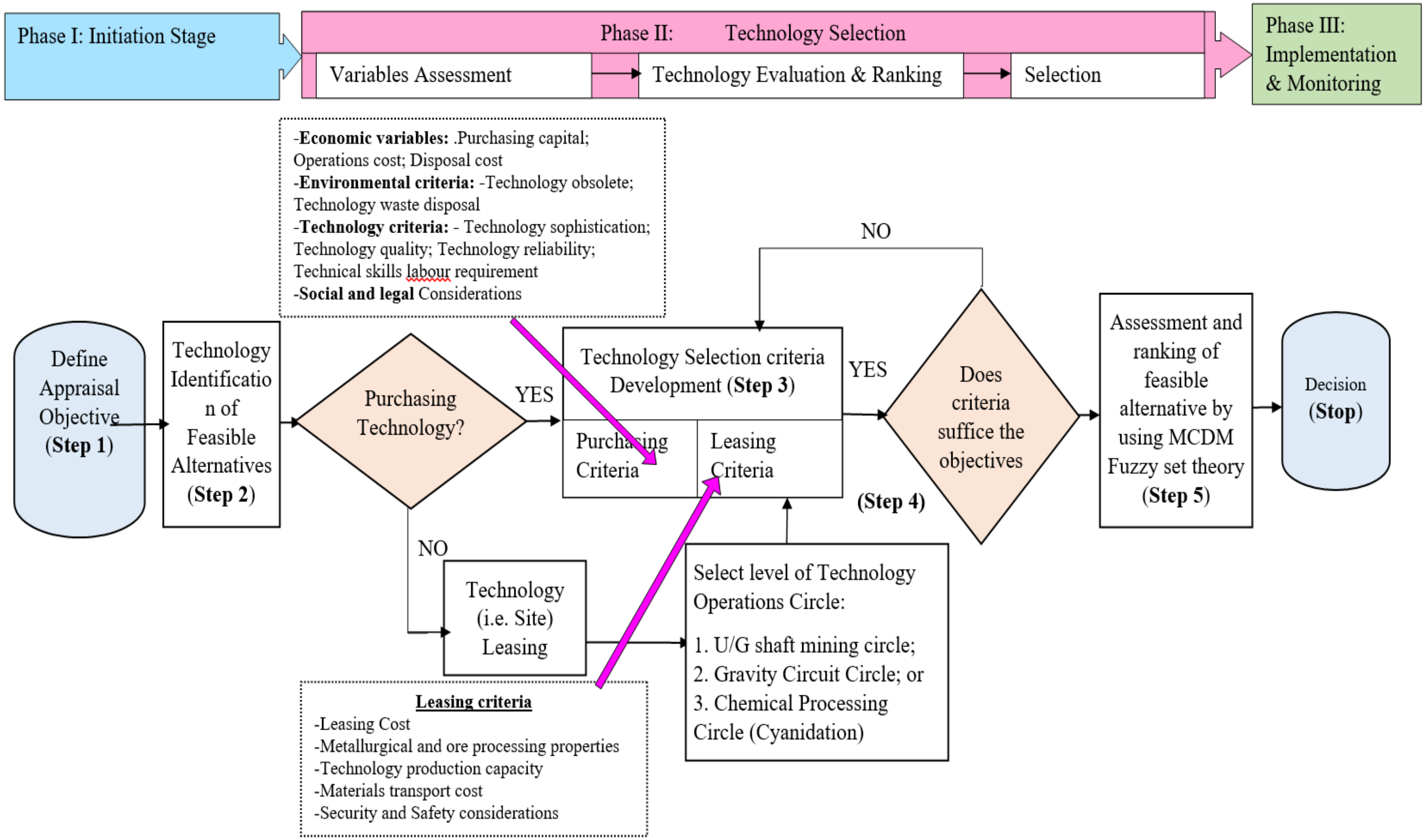


Figure 9: The proposed fuzzy based framework for sustainable technology selection in SSGM operations

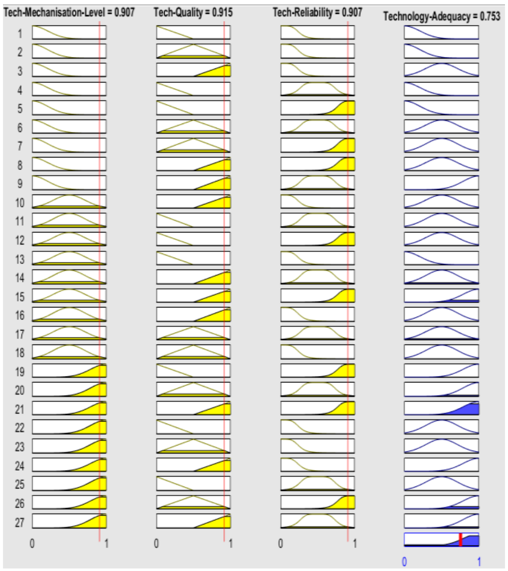


Figure 10(a): The rule view showing technical parameters on Technology adequacy.

The optimum results in Figure 10(c) shows that if the level of technology mechanisation is as below as 20% while the technology quality and reliability is high as above 82% and 62% respectively then the technology adequacy is above 60.5%. Similarly, Figure 10(d) shows the surface view that technology adequacy increases with the increase of both technology quality and reliability while mechanisation level decreases. Increasing the level of technology mechanisation results into increases technology mechanisation.

Mining and processing technology requires huge capital to acquire the technology and skilled personnel to operate. Therefore, the results on validation shows that technology assessment using framework provides the increase of technology adequacy as validity of function increases while keeping technology quality and reliability above 80%. to the results reflect that keeping the technology adequacy above 60% while level of mechanisation is below 20% and technology quality is 80% will make technology reliability to be above 60%.

The framework validation on economic value as shown in Figure 11(a) based on technology investment cost (Capex), Operation cost (Opex) and disposal cost selected economic criteria resulted to low economic value of 16.7% with high Capex, Opex and high disposal cost of 80.9% each criteria evaluated

Table: 4: Technology inputs and output variables for expert judgement

Input Variable	Output Variables	Evaluation Approach
Effect of Technology on Economic Aspect • Technology Capex • Technology Opex • Technology disposal cost	Economic value	Expert judgement on rating linguistic variables
Effect of Technology on Technical Aspect • Technology level of mechanisation (Technology Sophistication) • Technology quality • Technology reliability	Technology adequacy	Expert judgement on rating linguistic variables
Effect of Technology on Environmental Aspect • Technology obsolete • Technology disposal	Environment effects	Expert judgement on rating linguistic variables

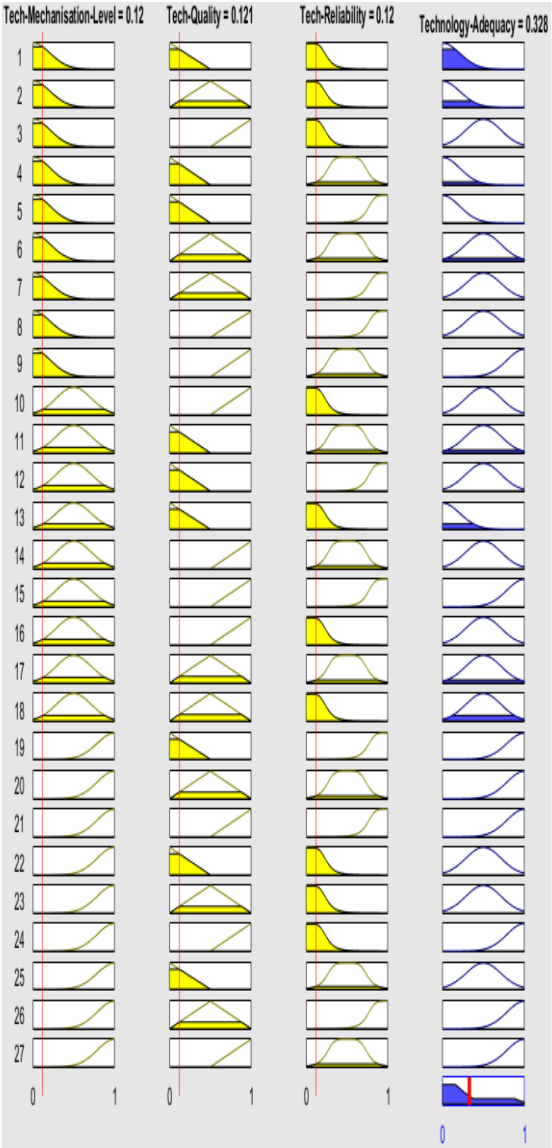


Figure 10(b): The Rule View Showing Parameters on Technology Adequacy. This should show different results.

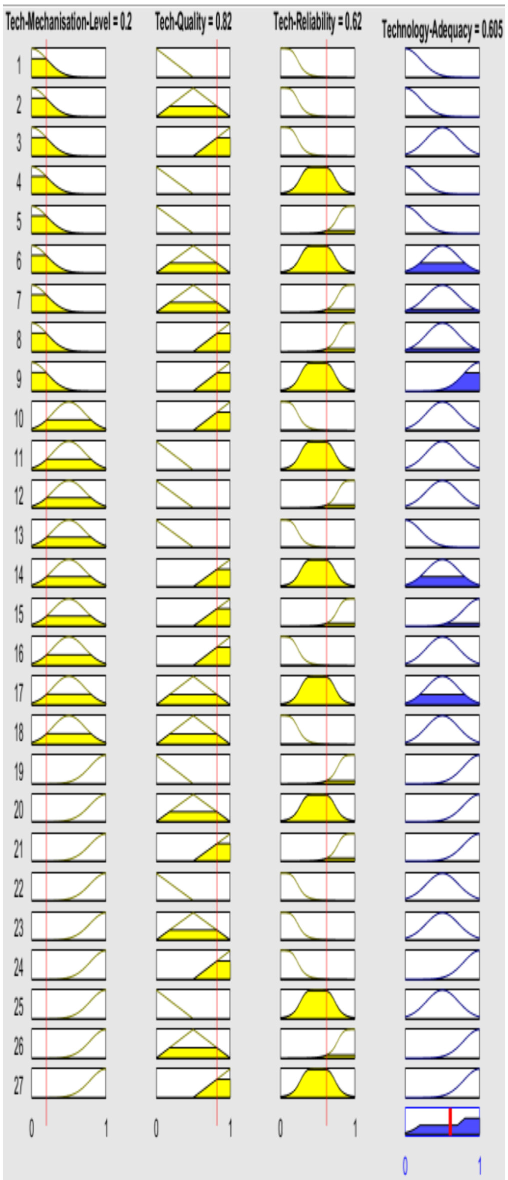


Figure 10(c): The rule view showing the evaluation of technical parameter effects on Technology adequacy (show different results)..

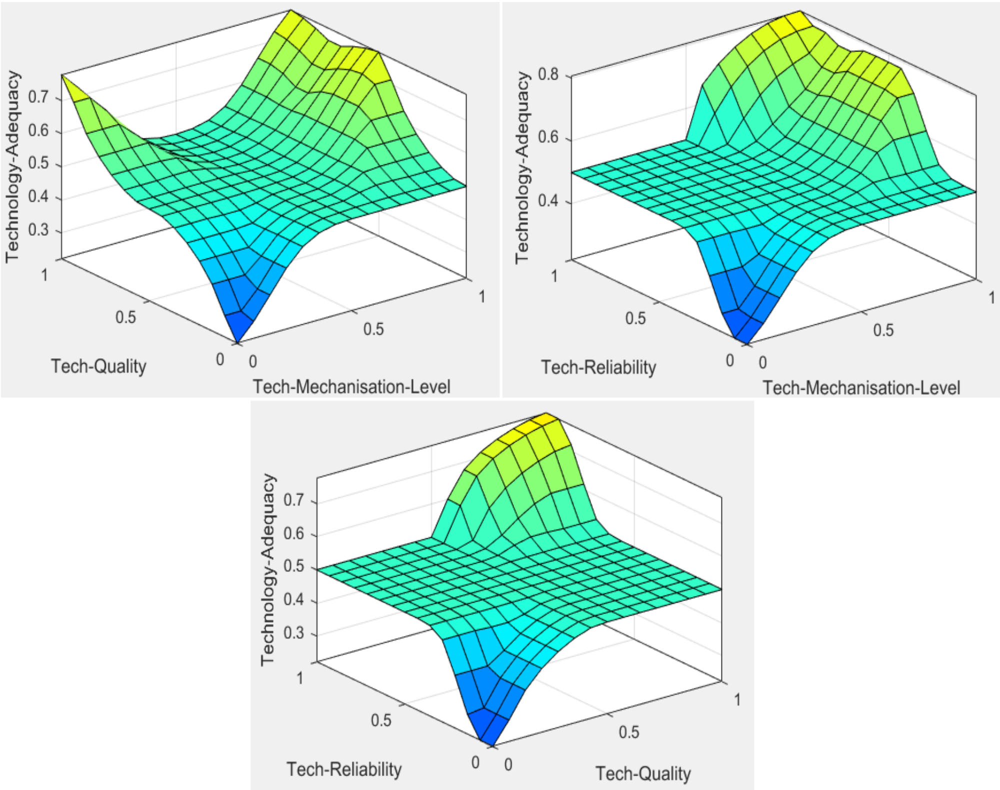


Figure 10(d): The surface view showing the results

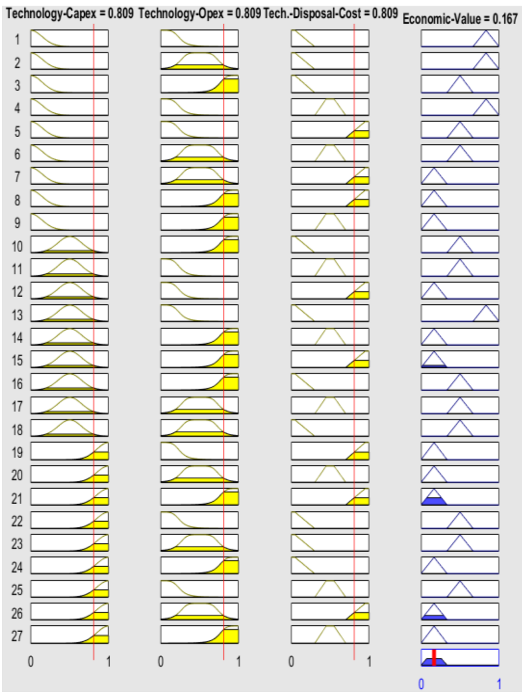


Figure 11(a): The rule view showing economic parameters low effects on the economic value

Similarly, Figure 11(b) shows that when economic criteria were at very low below 10.2% each their effects on economic value became very high 81.5%.

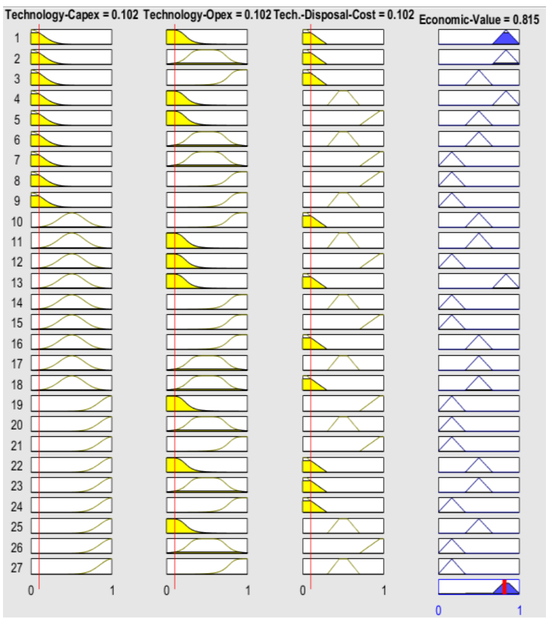


Figure 11(b): The rule view showing economic parameters high effects on the economic value

Figure 11(c) shows that for a project to be sustainably economically viable technology investment cost (i.e., Capex) should be of 65% to achieve an economic value of 66% while maintaining other costs at 28% and 25% for Opex and disposal cost respectively.

In Figure 11(d) the surface view shows that high economic value is achieved on decreasing operations cost (i.e., Opex) and disposal cost while increasing Capex from medium to high level and vice-versa.

The validation to check for the realistic effect of technology operating for the period of 50 years. Figure 12(a) shows the effect of technology depreciation and the disposal effect for such technology. The results show that technology obsolete of 48 years have a disposal effect of 90% results to moderate effects on the environment of about 48.6%.

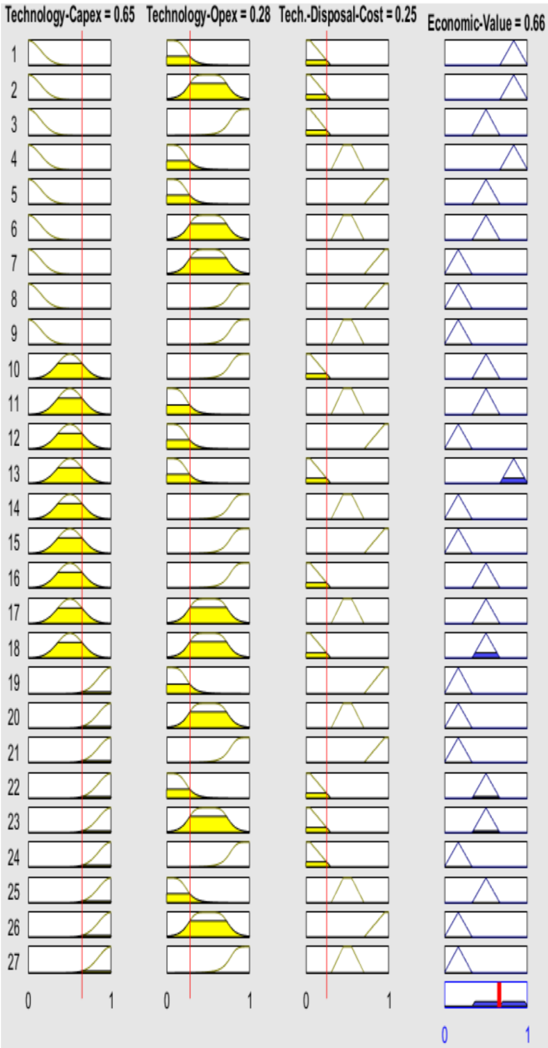


Figure 11(c): The rule view showing economic parameters effects on the economic value

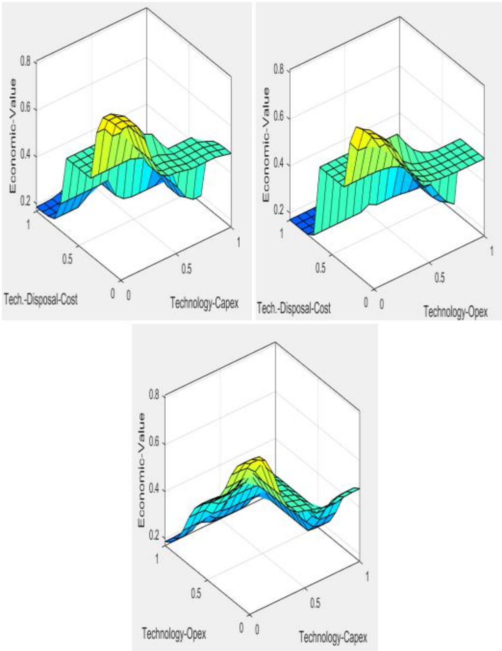


Figure 11(d): The surface view showing economic parameters effects on Economic Value.

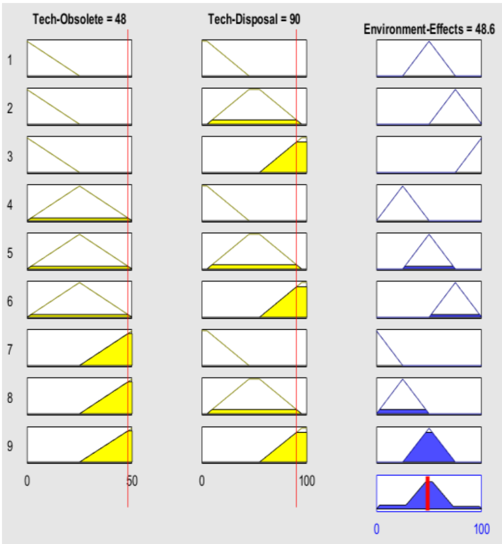


Figure 12(a): The rule view showing technology parameter effects on environment effects

Figure 12(b) shows that the technology obsolete and disposal effect of about 10.6% each then the effect on the environment found to be medium of about 43.6%.

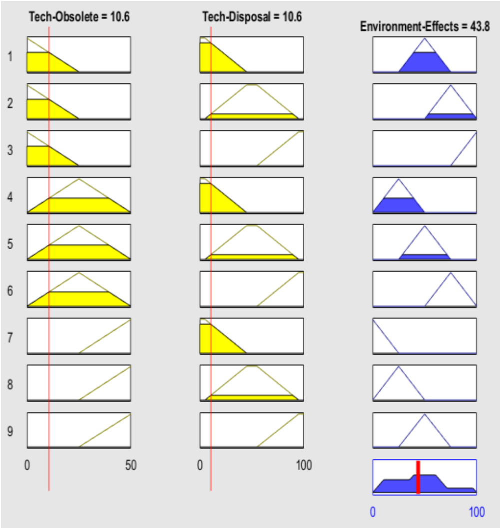


Figure 12(b): The rule view showing technology parameter effects on environment effects

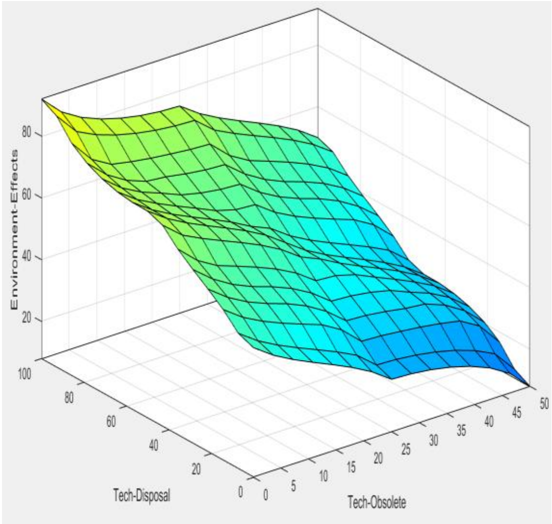


Figure 12(d): The surface view technology parameter effects on environment effects.

Figure 12(c) shows that technology equipment should have an obsolete period of about 45 years and technology disposal of low value less than 5% to have low disposal effect of less than 16% to the environment.

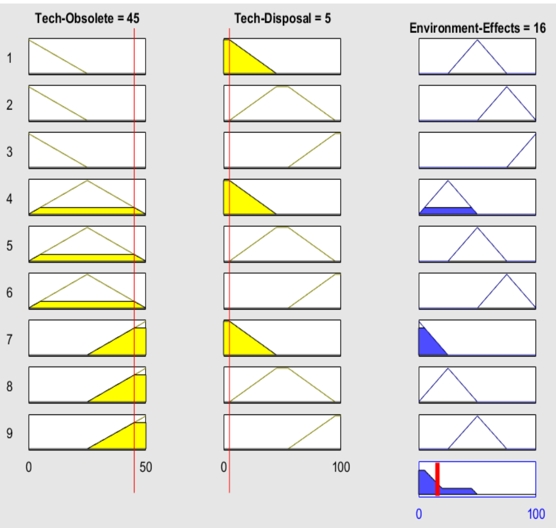


Figure 12(c): The rule view showing parameter effects on environment effects

Likewise, in Figure 12(d), the surface view of the fuzzy logic analysis result shows that on decreasing technology obsolete time, the effect on technology disposal increases and consequently the environmental effect increases.

Therefore, based on analysis, the framework provides a long period of technology usability before being disposed on the environment. This reduces the effect of dumping waste on the environment. Moreover, the optimal period for technology sustainability with low environmental effect occurs at 48 years of technology application with an obsolete of 98% cause waste on environment of 48.6% of the applied technology.

CONCLUSION AND RECOMMENDATIONS

The established fuzzy based framework for sustainable technology selection in SSGM operations is useful in identification, selection and evaluating small-scale gold mining technologies using the fuzzy tool. The framework as a guiding tool developed was validated by using the fuzzy logic tool in MatLab software.

A fuzzy based framework will be useful to help decision making process to select technology applied to underground shaft mining with square set timber, non-mechanized (purely manual) ore crushing, semi-mechanizing grinding (ball mill locally made), sluicing and panning for gold ore concentration, mercury amalgamation, and cyanide-chemical technologies.

The evaluation of technologies for non-mechanized ore crushing, manual sluicing and panning and mercury amalgamation processing technologies which recover gold from gold concentrates are not sustainable in consideration of economic, environmental and social pillars of sustainability as the technologies produces low yield, high wastes to the environment and poses high health risk to the nearby community. The limitation of the fuzzy based framework for such technologies is the application of fuzzy logic theory which requires the use of expert in selecting criteria and judgement for implementing multi-criteria decision making (MCDM) technique in evaluating and ranking of feasible alternatives.

The fuzzy based framework as a guiding tool for technology selection upon validation provided results that technology adequacy of more than 60% and the economic value of above 80% has low environment effect of about 16%. Similarly, technology obsolete of 45 years has a disposal effect on the environment of such technology of 5%. Therefore, for the small-scale mining sector to continue to bring economic advantages, application of pillars for sustainability considering economic, technical parameters and effect of technology on the environment is inevitable.

The managerial insights of the study recommend that the combined square-set timber and stull stopping mining technologies are suitable for the underground shaft and tunnel mining. Similarly, the SSGM should use the Semi-mechanised technology for ore size reduction for gravity technology processing circle. The use of semi-auto feed jaw crusher for ore crushing and ball mill for ore grinding is also proposed. Moreover, mercury-free chemical and cyanidation vat leaching processing technology are recommended. A study recommend also that policy makers and academicians should adopt the proposed framework and strengthen training to SSGM operators and decision makers on the use of fuzzy based framework so that miners can conduct mining activities sustainably.

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