Mining Methods Employed in Artisanal and Small-Scale Gold Mining and their Contribution Towards Sustainable Development of the Sector*

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Abstract

The selection of a suitable mining method for a particular ore deposit is an important attribute required for the environmental, safety and economic sustainability of a mining project. These multi-criteria decision-making process is a complex task for mining engineers as the selected method must suit the technical, economic, environmental and safety requirements of the mine. In Large-Scale Gold Mining (LSGM) operations, several mining methods have been developed and designed based on engineering principles to match the attributes of the various deposits exploited. However, in Artisanal and Small-Scale Gold Mining (ASGM), mining method development, selection and its implications on the safety, economic and environmental sustainability of the operations have been given little attention. This paper evaluates the mining methods employed in ASGM in Ghana and the contribution of the employed mining methods towards the sustainable development of the sector. The study employed a combination of literature review and field studies to ascertain the mining methods employed in ASGM. Relevant literature was retrieved from 2003 to 2022 from 4 scientific database namely, Academia, ResearchGate, Google Scholar and Google in August 2023. The field work involved the study of 4 ASGM sites in Tarkwa and Prestea. A total of 14 mining methods were identified to be employed in ASGM in Ghana. It was revealed that the identified mining methods were not designed or selected based on any engineering principles but rather the miners employed any abecedarian methods which result in ground failures subsequently leading to fatalities, environmental degradation and low ore recovery. The associated environmental degradation, poor safety and low productivity were indications that the mining methods employed in ASGM were hindering the sustainable development of the sector. Moreover, the study identified limited literature on mining methods employed by ASGM. It is therefore recommended that for sustainable development of ASGM in Ghana, researchers and experts should focus on developing and designing sustainable mining methods that will suit the various deposits exploited. It is also recommended that mining engineering and allied professionals should engage in ASGM to ensure effective implementation of the designed mining methods.

Keywords: Artisanal and Small-Scale Mining, Mining methods, Ore deposits, Sustainable development, Environment

1 Introduction

There is no globally accepted definition for ASGM as different countries, organisations and individuals have different approaches and concepts for defining ASGM (Amegbey *et al*., 1997; Avila 2003; Hentschel *et al*., 2003; Anon., 2012). Salati (2015) emphasised that the sector does not lend itself to any universal definition. Individuals, countries and organisations have based the concept of their definitions on the sizes of operations, capital investments, techniques of operations, number of workforces, concession sizes, reliability of operations, operational sustenance, management structure, output of the mine and legislative requirements (Eshun and Mireku-Gyimah, 2002; Hentschel *et al*., 2003; Anon., 2006; Anon., 2012). In developed countries, the sector has evolved into formal businesses which operate similarly to the LSGM operations except for the operational sizes (Hilson, 2003). However, in most developing countries ASGM operations are characterised with challenges regarding formalisation, techniques of operations, sustainability and the generation of intense negative environmental, safety, security and socio-economic impacts similar to that of any informal enterprise (Hilson, 2003).

ASGM operations which are noted to occur in 80 countries across Africa, Asia, Oceania, Central and South America are associated with a host of opportunities critical to the growth of various economies and critical to the attainment of the 2030 Sustainable Development Goals (SDGs) (Hentschel *et al.*, 2002; Hentschel *et al.*, 2003; Donkor *et al.*, 2006; Kessey and Arko, 2013; Bansah and Bekui, 2015; Asamoah and Osei-Kojo, 2016; Bansah *et al.*, 2016; Bansah *et al.*, 2017; Fritz *et al.*, 2018; Schwartz *et al.*, 2021). Contributions to economic growth come in the form of employment generation, gold production, revenue generation from the sale of the gold produced, taxes and royalties, licensing and permitting fees, promotion of local businesses, poverty alleviation, Corporate Social Responsibilities (CSR), community development and sustainability projects. and (Hentschel *et al.*, 2002; Hentschel *et al.*, 2003; Donkor *et al.*, 2006; Kessey and Arko, 2013; Bansah and Bekui, 2015; Asamoah and Osei-Kojo, 2016; Bansah *et al.*, 2016;

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Bansah *et al*., 2017). The availability of employment (estimated 44.5 million employments representing 90% of the total global gold miners) and the development of the rural communities has reduced the rural-urban migration problem (Fritz *et al*., 2018). Gold production from ASGM is estimated to be about 20% of the global total gold production with some countries experiencing significant increment over the years (Fritz *et al*., 2018). For instance, gold production from ASGM operations in Ghana have increased from 145 662 oz (6.29%) in 2000 to 2 130 155 oz (43.1%) in 2018 of the country's total production (Anon., 2020 Furthermore, the sector provides an alternative for mining smaller ore deposits which otherwise would not have been economically viable mining using large scale mining techniques.

Although ASGM plays a vital role in economic growth, the sector not seen much development in Ghana since its regularisation in 1989 as compared to the thriving Large Scale Gold Mining (LSM) sector (Bansah *et al*., 2016). The sector is faced with the problems of environmental degradation, poor safety and low ore recovery which arise from the use of inappropriate mining methods. The problem of unstable ground conditions emerging from the use of poor mining methods continues to persist as there are several reported cases of collapsed ASGM excavations often leading to fatalities (Anon., 2017; Anon., 2021; Anon., 2023). The lack of systematic approaches to mining results in high ore losses and dilution which gives rise to low revenue. When miners are faced with challenges of low ore recovery which translates to low profits or even losses, they mostly tend to relocate to other concessions or encroach on the concessions of LSGM operations. The shift from one concession to another leads to land degradation as the disturbed lands are mostly abandoned without reclamation. Moreover, such encroachments lead to conflicts between the Artisanal and Small Scale Miners (ASGMrs) and the LSGM operations (Yalley, 2020). Ghana as a country together with some global organisations such as the United Nations (UN), the World Bank have been pushing for the formalisation of the ASGM sector in a bid to promote sustainable development of the sector. However, such efforts have yielded minimal results as the formalisation strategies adopted have given little or no attention to the mining methods been used, the very acts which steer the environmental degradation, poor safety and low ore recoveries. It is therefore important that mining methods employed in ASGM be studied as this study shows a direct link between the mining methods employed and the sustainable development of the sector.

Surfeit research have been conducted in ASGM in the country to ascertain the challenges facing the sector and suggest possible ways to address them (Avila, 2003; Hilson and McQuilken, 2014; McQuilken and Hilson, 2016; Salati *et al.*, 2016; De Haan *et al.*, 2020; Franks, 2020). Many of these researchers have been quick to mention that the mining methods employed in ASGM were problematic and contributory factors to the associated environmental degradation and poor safety (Bansah *et al.*, 2016; Dumakor-Dupey and Bansah, 2017; Hilson and Maconachie, 2017). However, only a handful of such studies have mentioned or briefly explained the mining methods showing limited literature on the subject matter. Moreover, there is yet to be a study which explains in details the mining methods, evaluates the appropriateness of the mining methods for the deposit types exploited, brings out the causes of the environmental degradation, safety hazards and low ore recovery in the execution of the mining methods and shows the link between mining methods and sustainable development.

This study therefore seeks to fill that gap in by evaluating the various mining methods employed in ASGM and their contribution to the sustainable development of the sector. The outcome of this study will show the need for the Ghanaian government, Non-Governmental Organisations (NGOs) and global organisations such as the UN and the World Bank to promote the development and use of appropriate mining methods as strategies to formalise the sector. It will also stir up researchers and experts to focus on appropriate mining methods development for ASGM to promote sustainable development.

1.1 Principles of Mining Methods Development and Selection

Mining method can be defined as the systematic approach to liberate the mineable ore from the earth's crust. Mining method selection is the process of matching the characteristics of an orebody to the attributes of a mining method (Guray *et al*., 2003). The choice of a suitable mining method is important to the economics, safety and productivity of the mine as such the aim is to maximise profit without compromising on safety (Gupta and Kumar, 2012; Guray *et al.*, 2003; Shariati *et al*., 2013; Liu *et al.*, 2010; Ataei *et al*., 2008; Bogdanovic *et al.*, 2012; Popovic *et al*., 2019; Ye and Liu, 2012; Dehghani *et al*., 2017). There is no single mining method suitable for a particular deposit. The characteristics of a deposit make it feasible to employ two or more mining methods to mine. Therefore, an evaluation of the methods will be made to choose the one that will yield the most profit, has reduced costs (Capital and Operation costs), has higher productivity and better safety conditions (especially with regards to ground conditions) (Guray *et al*., 2003; Nieto, 2011; Liu *et al*., 2017).

There are several factors which are considered in the choice of the best mining method. Nieto (2011) classifies these factors into two categories namely Key Ore Deposit Indicators (KDIs) and Key Mining Method Indicators (KMIs). The KDIs refer to the characteristics of the deposit and the country rock such as: ore size, shape, width, dip, uniformity, ore strength, grade, depth below the earth crust and strength of the country rock. The KMIs refer to the performance of the various mining methods based on capital and operating costs, development time, production rate, mechanisation, selectivity and flexibility, health and safety and environmental impacts (Nieto, 2011). Knowledge of the KDIs and KMIs facilitates the mining method selection process. Gupta and Kamar (2012), also classify these factors as Intrinsic (factors associated with the deposit which are uncontrollable) and Extrinsic factors (factors which are not associated with the deposit and are controllable).

It is important for the best mining method to be chosen for a project because the use of a wrong mining method has the tendency to increase costs (capital and operating costs), render the mine unsafe, lead to economic losses and make the operations less productive and unsustainable. Moreover, attempts to change the mining method will be too expensive to implement and economically impossible (Dehghani *et al*., 2017). Due to the complexity of the mining method decision-making process and the effects of the parameters involved in operations, several methods have been developed to aid the mining engineer to make the correct choices.

LSGM operations depend heavily on the engineering-based developed mining methods to exploit the various deposit types being mined. In all these methods, there exist a mining schedule and infrastructural requirements to guide the successful execution of the mining methods. Fig. 1 and Table 1 summarise the deposit attributes suitable for Surface mining methods and Underground mining methods respectively.

1.2 Deposits Types Exploited for ASGM in Ghana

In Ghana the ASGMrs exploit gold occurring as Alluvial, Eluvial, Colluvial and Hard rocks (Alidu, 2017). Prior to the improvement in technology, the miners were mostly interested in alluvial, colluvial and eluvial deposits due to the ease of mining and ore processing. However, improvements in technology have seen miners exploiting hard rock deposits in the face of scarce alluvial, colluvial and eluvial deposits (Bansah *et al*., 2016). A clear case is that in the Northern regions of Ghana where the miners have to resort to mining hard rocks due to the scarcity of eluvial deposits. In many cases, alluvial, colluvial and eluvial deposits are all referred to as alluvial deposits. However, they are different in formations and occurrences. The sections below explain the characteristics of the deposit types exploited by ASGMrs in Ghana.

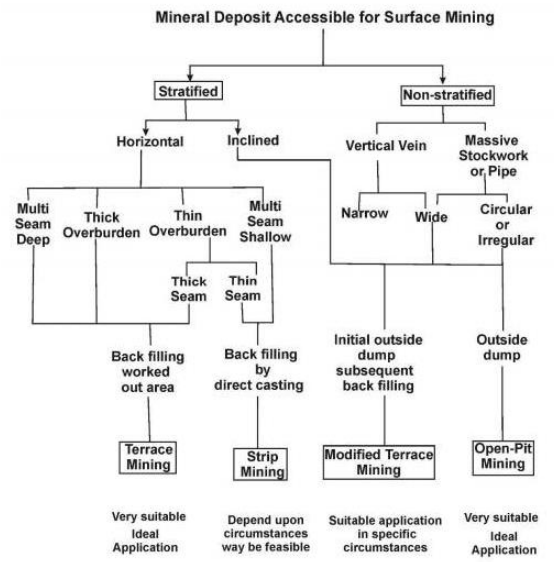

Fig. 1 Ore Deposit Characteristics Suitable for Surface Mining Methods (Source: Bullivant, 1987)

Table 1 Ore Deposit Characteristics Suitable for Underground Mining Methods

Underground methods	Unsupported				Supported		Caving		
Factor	*Room and Pillar*	*Stope and Pillar*	*Shrinkage Stoping*	*Sublevel Stoping*	*Cut and Fill Stoping*	*Square Set Stoping*	*Longwall Stoping*	*Sublevel Caving*	*Block Caving*
Ore strength	Weak / Moderate	Moderate/ Strong	Strong	Moderate/ Strong	Moderate/ Strong	Weak	Any	Moderate/ Strong	Weak/ Moderate
Rock strength	Moderate / Strong	Moderate/ Strong	Strong	Fairly Strong	Weak	Weak	Weak / Moderate	Weak	Weak / Moderate
Deposit shape	Tabular	Tabular / Lenticular	Tabular / Lenticular	Tabular / Lenticular	Tabular / Irregular	Any	Tabular	Tabular / Massive	Massive / Thick
Deposit dip	Low / Flat	Low / Moderate	Fairly Steep	Fairly Steep	Fairly Steep	Any	Low / Flat	Fairly Steep	Fairly Steep
Deposit size	Large / Thin	Any	Thin / Moderate.	Thick / Moderate	Thin / Moderate	Usually Small	Thin / Wide	Large Thick	Very Thick
Ore grade	Moderate	Low / Moderate	Fairly High	Moderate	Fairly high	High	Moderate	Moderate	Low
Ore uniformity	Uniform	Variable	Uniform	Uniform	Variable	Variable	Uniform	Moderate	Uniform
Depth	Shallow / Moderate	Shallow / Moderate	Shallow / Moderate	Moderate	Moderate / Deep	Deep	Moderate / Deep	Moderate	Moderate

(Source: Bullivant, 1987)

1.2.1 Alluvial deposits

Alluvial deposits in Ghana can be found in Bonsa, Wassa Akropong, Kwabeng, Manso Kran, Anyinam, Twifo Morkwa, Dunkwa, Jeninso, Awudua, etc. (Alidu, 2017; Foli *et al.*, 2020). They occur as gravels of streams, flats, and old valleys, on terraces and in beach gravels and sand. The thickness of the gravels range between 1 m to 6 m with barren silt and clay as the overburden (Alidu, 2017). These are placer deposits obtained from erosion and deposition of primary vein and lode-type Birimian deposits (Alidu, 2017).

1.2.2 Eluvial deposits

These deposits occur mostly in the Northern parts of Ghana and in Kanyankaw in Tarkwa. These deposits are formed when primary gold gets weathered, is carried and deposited by wind (Alidu, 2017). In the Northern parts of Ghana, eluvial ore processing involves the use of the winnowing due to the freely occurring gold liberated from the sulphide minerals. Moreover, the deposits are softer and permeable due to oxidation (Alidu, 2017).

1.2.3 Colluvial deposits

These are weathered rocks occurring as sand and gravels, mostly quartz gravels. The gold is not freely occurring, and thus require crushing and grinding before processing. These types of deposits are common in Winneba and Apam junction in Ghana.

1.2.4 Hard rock deposits

Alidu (2017) explained that this type of deposit is associated with gold bearing quartz which cuts sharply through the country rocks. Occurrence of such deposit are in Tarkwa, Prestea, Obuasi, some parts of the Eastern and Northen Ghana. The mineralised quartz veins are identifiable by the medium to dark grey colour. The width of the quartz veins range from a few millimetres to 2 m, with a depth of about 500 m or more (Alidu, 2017).

2 Materials and Methods Used

In order to evaluate the mining methods employed for ASGM operations in Ghana, the suitability of the methods for the various deposit types exploited, as well as the contribution to the sustainability of the sector, this research combined the use of literature review and field visits.

2.1 Materials and Methods Used for Literature Review

Relevant literature relating to mining methods exploited in ASGM were sourced from a variety of scientific databases namely; Academia, ResearchGate, Google Scholar and Google from 2003 to 2022 in August, 2023. These databases were chosen because they contain a wide variety of peer reviewed literature, with large citation and abstracting databases. The search title used to retrieve the data was "Artisanal and Small-Scale Mining Methods". A total of 21 relevant articles were manually sorted out from the individual databases. Out of the 21 articles, 14 duplicate articles were eliminated, therefore remaining 7 articles to review. The remaining 7 articles were further screened based on the abstract, methods and the results. A total of 3 articles were finally identified to fall within the inclusive criteria, that is this study focused on mining methods were being actually practiced in ASM sites. The other 4 articles Rupprecht (2017), Salati *et al*., (2016) and Quaicoe (2017) as cited in Anon. (2017) and Arthur-Holmes (2022) fell out of the inclusive criteria because they were either reviews of the mining methods already identified by the 3 relevant articles or proposed mining methods which were yet to be implemented.

2.2 Materials and Methods Used for Field Work

In order to access the mining methods used in ASGM and the sustainability of the methods, 4 ASGM sites were studied. The field work was concentrated in 2 towns in Ghana, Tarkwa in the Tarkwa-Nsuaem Municipal District and Prestea in the Prestea-Huni Valley Municipal District of Ghana. The study sites were purposively selected after consultation with the District officer of the Tarkwa Minerals Commission District Office to reflect the deposit types exploited in ASGM, Alluvial, Colluvial and Hard rocks. Unfortunately, there was no Eluvial mining site identified within these areas. Moreover, selection was done to represent both underground and surface mining operations. A total of 4 sites were selected out of which 2 were underground operations in Tarkwa whereas 2 were surface operations in Prestea. The 2 sites in Prestea were exploiting Alluvial and Colluvial deposits whereas the 2 sites in Tarkwa were exploiting hard rock deposits. The field visits were made between November and December 2022. The method used in the study include field observations, interactions with the miners and mine owners and supervisors.

2.2.1 Information About Study Sites

Tarkwa and Prestea were chosen for this study because of their mineral-rich contents and their long history of gold mining operations (both LSGM and ASGM). Dzigbodi-Adjimah and Asamoah (2010), stated that Tarkwa and Prestea districts happen to be the second and third largest producers of gold in West Africa after Obuasi.

Tarkwa

The Tarkwa town is located on Latitude 5° 18' 23.18" N and Longitude: -1° 59' 5.06" W. The town is accessible by road from Accra the capital town through Takoradi the Harbour city. It is located within the rainfall belt and has evergreen equatorial vegetation. Local geology of Tarkwa is basically of the Tarkwaian-type rocks. Much of the topmost part of the mountain ranges have weathering profiles exceeding 10 m therefore making exposures at the top quite uncommon. The Mohammed and Brothers Small scale mines and Dakete Small scale mines were chosen in Tarkwa for the study.

The Dakete mine is located in the southern portion of the northeast to southwest trending mineralised hill in Tarkwa. The concession is approximately 11 cadastral blocks; equivalent to 22.23 acres. Outcrops of the Dakete mine are of the Banket Series rocks of the Tarkwaian formation. These metasedimentary rocks are made up of three alternating quartzites and conglomeratic layers dipping moderately at about 35º. The topmost weathered portions of the concession are believed to be remnants of Tarkwa-phyllites. The Banket Series paleo-placer rocks contain gold deposits hosted in quartz-pebble conglomerates within the Tarkwaian formation. The Mohammed and Brothers small scale mine is located opposite Tardsco in Effuata. The mine has the same geological setting with Dakete mine, occurring on the same land stretch. The mine happens to employ over 800 workers. Many of the workers were contractors whose wage was to divide the ore mined with the concessionaires. The ore mined by the individuals within a gang was divided into 3 sacks, with the miners taking 2 sacks and the concessionaire given 1 sack.

Prestea

Prestea is bounded by latitudes 5° 26' 14.352" N and longitudes 2° 8' 24.4104" W. The town is located about 200 km from the capital Accra and 50 km from the coast of the Gulf of Guinea. It is accessible by road to Accra through a 6 hour drive through Takoradi, the Harbor city. Prestea has a tropical wet and dry (savanna) climate. The district’s yearly temperature is 27.44ºC (81.39ºF) and it is -1.42% lower than Ghana’s averages. Gold deposits in Prestea are made up of quartz veins and the disseminated sulphide. According to Dzigbodi-Adjimah and Asamoah, (2010), the quartz vein orebodies are generally of higher gold grades and lie within a graphitic gouge in the fissure zones whereas the disseminated sulphide are mostly located in sheared or crushed rocks near the fissure zones. Bazuri Small scale mine and an unlicensed site “galamsey” site were chosen for the study in Prestea. Interaction with the District Officer of Tarkwa Minerals Commission indicated that Bazuri mine was the only operational licenced ASGM site in Prestea. The other site used for the study was an illegal mining site with no name but with miners who were interacted with.

Bazuri mine concession forms part of a number of small-scale concessions which were created due to Legislative instrument in 2012 where all mining concessions were to conform to the Block System. The mine is located northeast of Prestea and is bounded by Latitudes 5º20'30'' N – 5º20'42" N and Longitudes 2º09'21'' W - 2º09'30'' W. Bazuri falls within the eastern channel reef of the Prestea Gold Belt precisely on the Tintinah block with a concession size of 10.50 acres. The concession falls within the rainforest bioclimatic zone but the rainforest within which the concession is located is devoid of primary forest currently due to logging, farming, historical mining activities that predate.

3 Results and Discussions

The study results have been grouped into 2 sections, the results from the literature review and results from the field studies.

The sections below give the results from the literature review and the field visits.

3.1 Results from Literature Review

A total of 3 articles, Aryee *et al.* (2003); Eshun (2005) and Bansah *et al.*, (2016) were found to be relevant to the subject matter. Results from the review have been given in the sections below. Table 2 is a summary of the mining methods identified in the selected articles.

Table 2 Summary of Mining Methods Employed in ASGM in Ghana

AUTHORS	MINING METHODS	DEPOSIT TYPES
Aryee *et al.* (2003)	Shallow Alluvial Mining	Alluvial Deposits
	Deep Alluvial Mining	
	Hard Rock (Lode) Mining	Hard Rocks
Eshun (2005)	Surface Mining	Alluvial deposits or other deposit types close to the earth surface (usually outcropping)
	Underground Mining	Hard rocks in abandoned shafts, pits and adits
Bansah *et al.* (2016)	Anomabo Method	Alluvial gold deposits in river beds
	Dredge Method	
	Dig and Wash	Shallow Alluvial deposits occurring in river banks, valleys, terraces and tailings of abandoned mines
	More Blade Method	Deep Alluvial deposits
	Alluvial Washing Plant	
	Chisel and Hammer	Hard rocks (lode) outcropping
	Underground Ghetto	Hard rocks in old abandoned mines

(Sources: Aryee *et al.* (2003); Eshun (2005); Bansah *et al.*, (2016))

3.1.1 Mining Methods Identified in Literature

Results from the literature review indicated 12 mining methods exploited for mining alluvial and hard rock ore deposits. The sections below describe the deposit types exploited using the mining methods, operational cycles, technology and the sustainability challenges encountered using the above-mentioned mining methods. The methods have been presented based on the findings of the 3 Authors.

Surface mining method

The Surface mining method was identified by Eshun (2005) to be employed on all deposits types which are outcropping or shallow buried. The first step of operation according to Eshun (2005) is to locate an outcrop, the vein or mineralised zone. Once that has been located, the miners mine along the course of the mineralised zone to depths that are allowable by the available technology. Mining sequence involves the removal of overburden and mining of the ore to the processing sites (Eshun, 2005) The miners at times divert the courses of rivers and streams to mine the materials at the banks up to about 10 m and beyond. In all it can be seen that the surface mining methods as explained by Eshun (2005) were mostly those around water bodies. Due to the water pollution associated with such methods, these methods are prohibited in Ghana. The laws only permit mining within or beyond 100 m reach from water bodies in the country.

Underground mining method

Underground mining is the second mining method identified by Eshun (2005) which is employed for mining hard rock deposits in abandoned shafts, pits and adits. Majority of such operations were initially owned by some LSGM companies. The already existing excavations such as shafts, adits, tunnels and level accesses make it easy and inexpensive for the ASGMrs to exploit the underground excavations. However, Eshun (2005) emphasised that the miners are unable to exploit the ore at greater depths due to the limitations of technology, ventilation, lighting and drainage. The use of chisels, hammers, mattocks and shovels for rock fragmentation reduces the productivity of the operations. In some cases, the hardness of the rocks may make it impractical to fragment using chisels, hammers, mattocks and shovels. Major challenges regarding this method are poor ventilation and unstable grounds. Insufficient air supply and fumes from the explosives after blasting may result in suffocation and eventual deaths. Also, ground failures may lead to fatalities.

Anomabo method

This surface mining method which is fading out is a typical manual dredging technique of mining involving the scooping of gold bearing gravels deposited at the river beds (Acheampong, 2009). It is practiced after the rainy season when loose mineralised ore materials have been washed and deposited in the river beds. With a minimum crew of 2 persons, mining can take place (Bansah *et al*., 2016). The mining cycle consists of scooping, hoisting and hauling to processing site. Simple tools such as a scoops, buckets, shovels and sacks are employed in mining.

It requires minimal capital cost and operating cost. However, it is associated with low productivity due to the manual nature of operations and could be highly risky in terms of the operator diving to scoop the material. It is also a seasonal method which could only be practiced after the rainy seasons, signifying that it will be impracticable during the dry season. Moreover, the scooping of water from the riverbeds highly pollutes the water and increases the turbidity of the water. In cases where the rivers are the only sources of water supply, the inhabitants, flora and fauna will be heavily affected by the pollution of water.

Dredge method

This is a mechanised version of the Anomabo method, where suction dredges are used to excavate the sedimentary ore deposits from the streams or river beds. Operations are similar to the conventional large scale dredging method however, the suction dredge is locally manufactured from discarded metals and powered by changfa motors (Bansah *et al*., 2016). Mining sequence involves the suctioning of the ore deposits and transporting it hydraulically onto sluice boards mounted at the processing plant. Due to the mechanised nature of operations, a few mining crew of about 5 individuals could engage in mining (Bansah *et al*., 2016). Productivity here is higher than the Anomabo method due to the mechanisation of operations. However, it is not sustainable environmentally due to the associated water pollution. Fig. 2 below shows the dredging method as employed by ASGMrs in Ghana.

Dig and wash method

This is a shallow alluvial mining technique which is used in mining shallow alluvial deposits occurring on river banks, in valleys, on terraces or in the tailings dump of abandoned mines (Bansah *et al*., 2016).

Fig. 2 Dredging Method (Source: Anon., 2009)

Mining sequence involves the clearing of vegetation, topsoil and overburden removal, mining of ore material and loading into sacks and transporting to the processing site (Bansah *et al*., 2016). This method is labour intensive with the use of simple tools such as shovels, pickaxes and spades. It requires low capital and operating cost with few mining crew members to operate. It degrades vast land areas as mining usually progresses laterally. Fig. 3 below shows the dig and wash method.

Fig. 3 Dig and Wash Mining Method (Source: Anon., 2009)

"More blade" method

This is a semi-mechanised mining method, a modification of the dig and wash mining method. The mining process is mechanised with the use of excavators to load the materials from the pit to a stockpile. The stockpiled materials are then rehandled with shovels unto sluice boards for washing. Bansah *et al.* (2016) explained that the method is mostly practiced in areas closer to streams or rivers to provide the water for the washing. This method is labour intensive especially at the processing stage where more individuals are required for the loading and washing (Bansah *et al.*, 2016). Moreover, it is associated with massive land degradation making it not sustainable environmentally.

Alluvial washing plant

This is currently the most commonly used ASGM method in Ghana and other parts of the world (Bansah *et al.*, 2016). The mining process is mechanised involving the use of excavators to load the loose materials unto trucks to be hauled to the processing site. In cases where the processing site is close to the mine site, direct hauling is done by the excavator. The term "Alluvial Washing Plant" is generated from the fact that the washing plant is the equipment used in processing the ore. In the ore processing, a second excavator is employed to load the stockpile material into the washing plant (Bansah *et al.*, 2016). In many cases, other auxiliary equipment such as dozers and graders are used to help push materials and for haul roads maintenance. This method is environmentally sustainable when it is combined with the direct smelting technique and a 3-pond purification system, as well as with a proper tailings and waste management system in place.

Mechanisation of the mining process gives rise to high productivity. However, the acquisition of the mining equipment or rental charges of the mining equipment are mostly beyond the financial reach of the mine owners. Moreover, the maintenance costs of the equipment and operating costs of are higher. As such, high operational costs require higher grades mineral reserves should to make up for the high operational costs. Fig. 4 shows the Alluvial washing plant method as practiced in Ghana.

Chisel and hammer method

This method is applicable to hard rock (lode) formations which are either outcropping or are shallow buried within the earth crust (Tepkor, 2005). Mining sequence involves the clearing of vegetation, topsoil and overburden removal and mining of the ore. This is a manual technique which employs the use of chisels and hammers to fragment the ore material, hence the name "chisel and hammer".

Fig. 4 Alluvial Washing Plant Method (Source: Anon., 2015)

The broken ore materials are loaded into sacks with the use of shovels and transported to the processing plant. The broken ore is first crushed and then grinded into powder form for sluicing. Crushing and grinding may be achieved with the use of mechanical crushers and grinders or manually achieved with the use of mortars and pestles (Bansah *et al.*, 2016). The mercury amalgamation technique employed makes the process environmentally unsustainable. Besides, the manual technique is associated with low productivity even though the capital cost and operating costs are low. Moreover, this method is highly hazardous as the chiseling and hammering process exposes the miners to dust and the risk of rock particles getting into contact with the eyes or skin. Fig. 5 shows a miner engaged in Chisel and hammer method.

Fig. 5 Chisel and Hammer Method (Source: Anon., 2009)

Underground "ghetto" method

The underground method also known as "ghetto" method is applied to hard rock formations occurring about 15m and beyond below the earth surface. These are deep seated deposits which usually may have been worked on by old and abandoned mines (Bansah *et al*., 2016). The ore deposits are accessed by means of adits, tunnels or shafts which are sunk from the surface of the earth. Mining process involves creating accesses to the ore deposits and subsequently fragmenting the ore with chisels and hammers. In rare cases, the mining laws allow ASGMrs to blast the rocks using explosives. Otherwise, in many cases ASGMrs are forbidden from the use of explosives. Even in cases where they are allowed, blasting will have to be approved by the Minister of Lands and Natural Resources upon recommendation from the Minerals Commission plus it should be carried out by a certified blastman (Anon., 2012).

The fragmented materials are loaded into sacks using shovels and carried to surface by the miners to be processed. This method is highly labour intensive, tedious and associated with many risks. Moreover, the quantity of materials mined at a time is relatively small, as such the grades should be high to make up for the costs of operations. The possibility of ground failures, accumulation of fumes and dust and excessive heat makes this method highly unsafe. Fig. 6 shows an ASGM underground shaft with a miner descending it.

Fig. 6 A Miner Descending an ASGM Underground Shaft (Source: Anon., 2017)

Shallow Alluvial Mining

Shallow alluvial mining techniques, as identified by Aryee *et al*. (2003) is the same as the "dig and wash", method as explained by Bansah *et al.* (2016). The mode of operations and the sustainability challenges are the same as the ones mentioned in section 3.1.1.5 above.

Deep Alluvial Mining

Aryee *et al*., (2003) identified Deep alluvial mining method as one used for mining deep alluvial deposits found along the banks of major rivers and older river courses. It applicable to mine gold bearing gravels occurring about 7 to 12 m within the ground. As such mining involved the stripping of an overburden of about 7m thickness to reach the gold bearing gravel. This is a form of open pit mining where terraces or benches are constructed to avoid collapse of excavations (Aryee *et al*., 2003).

Hard Rock Mining

Hard rock mining as observed by Aryee *et al*. (2003) is adopted to mine shallow or deep-seated gold bearing reefs. This mining method as described by Aryee *et al*. (2003) is similar to the Chisel and Hammer method and Underground "Ghetto" method as described in sections 3.1.1.8 and 3.1.1.9 respectively.

3.1.2 Evaluation of the Sustainability of the Mining Methods in Literature

The sustainability of the mining methods available in literature have been evaluated based on based on environmental, safety and productivity parameters. The results of the evaluation have been summarised in Table 3 below.

Table 3 Summary of the Sustainability of the Mining Methods in Literature

MINING METHODS	ENVIRONMENTAL DEGRADATION	SAFETY HAZARDS	ECONOMIC SUSTAINABILITY
Shallow Alluvial Mining	Vast lands degraded as mining progresses laterally.		Highly labour intensive with low productivity.
Deep Alluvial Mining	Land degradation and water storing in pits	Stable walls due to benching. Water left in pits serve as death traps.	
Hard Rock (Lode) Mining		Ground failures leading to fatalities. Suffocation from insufficient ventilation, dust or fumes from blasting. Poor illumination and drainage.	Limited technology to access higher grade orebodies at greater depth
Surface Mining	Mining in or close to rivers and streams, results in water pollution.	Undercutting of materials without benching may result in collapse.	Productivity restricted to affordable technology
Underground Mining		Ground failures leading to fatalities. Suffocation from insufficient ventilation, dust or fumes from blasting. Poor illumination and drainage.	Limited technology to access higher grade orebodies at greater depth
Anomabo Method	Mining in rivers and streams, results in water pollution.	Diving in water may lead to drowning of individuals.	Low productivity and seasonal operations.
Dredge Method	Use of dredges in rivers and streams results in high levels of water pollution.		Higher productivity due to the mechanisation
Dig and Wash	Vast lands degraded as mining progresses laterally.		Highly labour intensive with low productivity.
More Blade Method	Vast lands degraded as mining progresses laterally.		Highly labour intensive especially at the point of ore processing with low productivity.
Alluvial Washing Plant	Problems of waste water management from the plant exist. Vast lands degraded due to lateral progress of mining.	Water forms ponds on lands serving as death traps.	Acquisition or rental of equipment is expensive, as such ore grades should be high enough to cater for costs.
Chisel and Hammer		Undercutting of materials without	Low productivity due to the manual operations
Underground Ghetto		Ground failures leading to fatalities. Suffocation from insufficient ventilation, dust or fumes from blasting. Poor illumination and drainage.	Limited technology to access higher grade orebodies at greater depth

3.2 Results from Field Visits

3.2.1 Bazuri small scale mine

At Bazuri, the deposit types being worked on are both alluvial and colluvial deposits. The mine practices Open pit mining method, however, there are no designs or plans being used to execute the operations. Material movement involved excavation of the topsoil together with the overburden and depositing just around the pit or in some cases within the pit. There was no out of pit dump to stockpile the topsoil or to dump the waste or low grade material. There were no benches used but a single long steep slope about 30 m long inclined at about 85°. On many occasions, the mine had recorded slope failures but was lucky not to record any fatality or equipment damage. Due to the loose nature of the materials, there was no need for blasting to fragment the material. Material handling was done using an excavator-truck system to move the ore to an out-of-pit processing site. Water collected at the pit bottom was pumped out of the pit. Fig. 7 (a, b, c, d) show the images of the Bazuri pit slope walls, accumulated water at the bottom of the pit, the excavator and dump truck used at the mine.

From the observations made at the mine, it could be concluded that the mining method employed was not sustainable. There were so much materials scattered within and around the pit. Moreover, the failing pit walls was a major safety concern. In addition, the mixing of the various materials types would make reclamation difficult as there will be no topsoil to support vegetation The mine requires proper mine design and plans that are in conformity with the orebody characteristics to ensure optimisation and sustainability. Whereas officials in the mine had knowledge about the mining method being used, it was admitted that the mine had to acquire a geological model for proper mine plans and design

Fig. 7 (a) Bazuri Pit Slope Walls, (b) Accumulated water at the Bottom of the Pit, (c) An Excavator Used at the Mine, (d) A Dump Truck Used at the Mine

3.2.2 Mining method at the "Galamsey" site

The mining method practiced at the galamsey site at Prestea was similar to that of Bazuri mine. The open pit had a steep slope of about 90° with a single slope of about 40 m long. Materials mined were solely alluvial materials. This mine was solely a manual operated site with the use of shovels and pans for the material movement. There were some sheds erected to house the generator that pumps the water from the pit bottom. The unstable pit walls represented a typical ASGM site in Ghana which had the likelihood of failure leading to fatalities. Besides, there is also the likelihood that the open pit will not be backfilled, thereby leaving dangerous excavations after mining. The mine site was characterised by poor housekeeping, failing walls and flooding in the pit. Fig. 8 shows an open pit of the galamsey site at Prestea.


Fig. 8 Open Pit at the Galamsey Site at Prestea

3.2.3 Mohammed and Brothers Mine

This is a hard rock underground mine utilising both an adit and a shaft system as the means of entry. The hard rocks are outcropping with quartz veins as the mineralisation. The mine practiced inclined room and pillar mining since the deposits were flat bedded at an angle of about 15°. This was an abandoned mine and as such had the underground mine accesses already created. The mine managers as well as the miners had no idea about mining methods or the selection and the implication on the mine. In all, the rooms and pillars were created based on their discretion and not based on any engineering principles or designs. Timbers were mostly used to support the roofs and, in some cases, waste materials were used to fill the rooms. The miners were limited to only level 5 due to the availability of technology to mine the deeper deposits. There was no idea of the total reserve or resource as no proper exploration programme had been carried out. Therefore, the miners operated in a "trial and error" mode with the main aim of following the course of the vein. The major challenges facing the mine are ventilation, ground supports, drainage and cost of electricity. The ventilation is so bad that some of the miners admitted that some of their colleagues had died due to poor ventilation at the work site but such cases were not reported. The mine also experienced occasional flooding due to pump failures. The timbers were not competent enough to support the grounds as the timbers were mostly wet and susceptible to decay. Fig.s 9 (a, b, c, d) show an adit at the mine, the mine shaft with rails, the room and pillar mining and timber supports respectively.

3.2.4 Dakete Company Limited

The mining method was not particularly selected, but merely, an imitation of the system that was prevalent at the advent of the small-scale operation; room and pillar mining system. The current method of mining employed at the mine is a continuation of the room and pillar method formerly implemented by Goldfields Limited, the pioneer concessioners, in tandem with manual chiselling of the visible mineralised reefs. The room and pillar method at Dakete Company Limited mainly involves mining of abandoned underground workings. In this method, manual chiselling replaces the conventional drilling and blasting as a means of rock breakage. After which ore is gathered into sacks and transported on the backs of workers to the surface for processing.

It was revealed through discussions with the mine officials that there were no specific mine plans or designs followed in the exploitation process. Even though some parameters were stated as the pillar and room geometry, observations of the rooms and pillars showed that the room sizes and pillar sizes were not uniform as initially communicated. Some rooms were as wide as 5 m and about 15 m whereas the pillars were about 2 m wide. While exploration and development have been long handled by the pioneer concessioners, Goldfields Limited, the data gathered through interviews revealed that little was done in terms of exploration, development and grade control in the implementation of the room and pillar mining system. Although, samples are occasionally taken and washed in a "sample tyre" to depict the mineral worth of the active mining area. Fig.s 10 (a, b, c, d) show timber supports for the roof of the rocks, an adit at the mine, the room and pillar mining method and a pillar left between rooms at Dakete mine respectively

Fig.s 9 (a) An Adit at the Mine, (b) The Mine Shaft with Rails, (c) The Room and Pillar Mining Method, (d) Timber Supports Underground at Mohammed and Brothers Mine

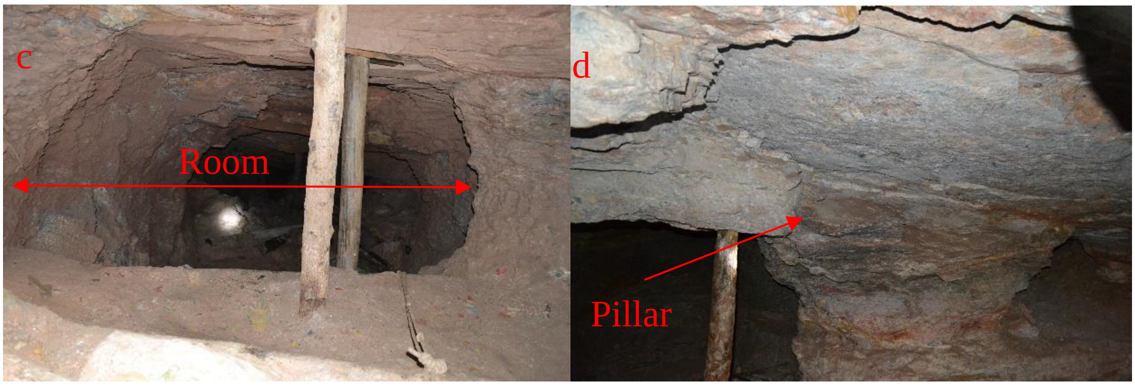

Fig.s 11 (a) Timber Supports for the Roof of the Rocks, (b) An Adit at the Mine, (c) The Room and Pillar Mining Method, (d) Pillar left Between Rooms at Dakete Mine

3.3 Comparative Analysis of Results from Literature Review and Field Studies

Table 4 shows a comparative analysis of the results obtained from the Literature review and the field studies.

Table 4 Comparative Analysis of Results from Literature and Field Studies

ITEM	RESUTS FROM LITERATURE REVIEW	RESULTS FROM FIELD STUDIES
Number of Mining Methods Identified	12 methods stated but 2 were duplicate methods	2 identified methods
Name of Identified Mining Methods	Shallow Alluvial Mining, Deep Alluvial mining, Hard rock (lode) mining, Surface mining, Underground mining, Anomabo method, Dredge method, Dig and wash, More blade method, Alluvial washing plant, Chisel and hammer and Underground "ghetto" method	Open pit mining and Room and pillar mining
Deposit Types Exploited	Alluvial and hard rock deposits	Alluvial, colluvial and hard rock deposits
Engineering of Mine with Mine Plans and Designs	No mine designs or plans used	No mine designs or plans used
Environmental Issues	Problems of water pollution resulting from mining in or close to water bodies and effluents discharge into water bodies. Associated with massive land degradation.	Land degradation only prominent on the "galamsey" site. Waste water management was a challenge. However, the effluents were contained.
Safety Hazards	Ground failures leading to fatalities. Suffocation from insufficient ventilation, dust or fumes from blasting. Poor illumination and drainage. Water left in pits after mining serve as death traps.	Problems of slope failures, poor ground supports and unstable grounds. Poor ventilation leading to suffocation and eventual deaths. Poor illumination and mine drainage.
Economic Sustainability	Limited technology, "trial and error mining" and labour-intensive nature results in low productivity	Limited technology, insufficient geological data, absence of mine designs and plans results in a "trial and error" mining pattern with low productivity.

4 Conclusions and Recommendations

4.1 Conclusions

The study employed the use of literature review and field studies to identify the mining methods employed in ASGM in Ghana. Results from literature revealed 12 mining methods out of which 2 were identified to be duplicates. Results from literature revealed that Alluvial and Hard rock deposits were exploited using the above-mentioned mining methods. The field studies revealed 2 mining methods used to Alluvial, Colluvial and Hard rocks exploited for ASGM operations in Ghana. It was observed from the field studies that the ASGMrs who worked in abandoned underground mine sites usually maintain the mining methods being used by the previous companies. However, they lacked the technology to exploit the deeper deposits and explore for more resources. The sustainability of the mining methods were evaluated based on environmental, safety and economic considerations. It was observed that all the mining methods resulted in some forms of environmental and safety disbenefits. As such the methods were not environmentally sustainable and safe. In terms of economic considerations, it was identified that limited technology, insufficient geological information, absence of mine plans and designs and the labour-intensive nature of the methods resulted in low productivity. It can be concluded that the mining methods employed in ASGM are hindering the sustainable development of the sector

4.2 Recommendations

It is therefore recommended that for promotion of sustainability of the sector, the mining methods employed should be given attention by the various stakeholders. Further studies should address this gap by developing and designing mining methods that will promote environmental, safety and economic sustainability of the sector. Moreover, governments, NGOs and international organisations seeking to formalise the ASGM sector should promote the use of appropriate mining methods. In addition, there should be a conscious effort to integrate mining engineering and allied professionals into the ASGM sector to ensure effective development and implementation of the mining methods.

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References

Acheampong, K. A. (2009), "Development of Small-Scale Mining Methods and their Impacts on the Environment of the Tarkwa Area", *Unpublished BSc Project Work*, University of Mines and Technology, Tarkwa, Ghana, pp. 10 – 22.

Alidu, S. (2017), "Basic Geology– A Guide to Discover Mineral Deposits", *Artisanal and Small-Scale Mining Handbook for Ghana*, Geological Survey of Denmark and Greenland, pp. 28 – 37.

Amegbey, N. A., Dankwa, J. B. K. and Al-Hassan, S. (1997), "Small-Scale Mining in Ghana – Techniques and Environmental Considerations", *International Journal of Surface Mining, Reclamation and Environment*, Vol. 11, No. 13, 8 pp.

Anon. (2006), *Minerals and Mining Act, 2006*, Ghana Publishing Company, Ghana, pp. 44 – 50.

Anon. (2009), "Small Scale Mining", *https://researchgate.org*, Accessed: September 25, 2023.

Anon. (2012), *Analysis of Formalisation Approaches in the Artisanal and Small-Scale Gold Mining Sector Based on Experiences in Ecuador, Mongolia, Peru, Tanzania and Uganda*, United Nations Environment Programme Committee Report, Geneva, Switzerland, 14 pp.

Anon., (2017), *Artisanal and Small-Scale Mining Handbook for Ghana*, Geological Survey of Denmark and Greenland, pp. 28 – 37.

Anon. (2020), "Ghana Chamber of Mines Mining Industry Statistics and Data 2020", *www.ghanachamberofmines.org*, Accessed: July 5, 2023.

Anon. (2021), "Nine Confirmed Dead in Gbane Mining Calamity", *https://gna.org.gh*, Accessed: October 20, 2020.

Anon. (2023), "At Least 7 Killed in Ghana Mining Pit Collapse", *https://english.news.cn*, Accessed: October 20, 2023.

Arthur-Holmes, F., Busia, K. A., Yakovleva, N. and Vazquez-Brust, D. A. (2022), "Artisanal and Small-Scale Mining Methods and the Sustainable Development Goal 6: Perceived Implications for Clean Water Supply", *Environmental Science and Policy*, Vol. 137, pp .205-215.

Aryee, B. N, Ntibery, B. K. and Atorkui, E. (2003), "Trends in the Small-Scale Mining of Precious Minerals in Ghana: A Perspective on its Environmental Impacts", *Journal of Cleaner Production*, Vol.11, No. 2, pp. 131 – 140**.**

Asamoah, K. and Osei-Kojo, A. (2016), "A Contextual Analysis of Implementation Challenges of Small-Scale Mining Laws in Ghana: A Case Study of Bekwai Municipality", *SAGE Journal*, Vol. 10, No. 11, 11 pp.

Ataei, M., Jamshidi, M., Sereshki, F. and Jalali, S. (2008), "Mining Method Selection by AHP Approach", *Journal of the Southern African*

Institute of Mining and Metallurgy, Vol. 108, No. 12, pp 741-749.

Avila, E. C. (2003), "Small-Scale Mining: A New Entrepreneurial Approach", *Natural Resources and Infrastructure Division*, United Nations Publication, Santiago, Chile, 79 pp.

Bansah, K. J. and Bekui. P. (2015), "Socio-Economic and Environmental Assessments of Illegal Small-Scale Mining in Ghana", *8th International African Materials Research Society Conference*, Accra, Ghana, pp. 276.

Bansah, K. J., Yalley, A. B. and Dumakor - Dupey, N. (2016), "The Hazardous Nature of Small-Scale Underground Mining in Ghana", *Journal of Sustainable Mining*, Vol. 15, No. 1, 18pp.

Bansah, K. J., Dumakor-Dupey, N. K., Sakyi-Addo, G. B. (2017), "Digging for Survival: Female Participation in Artisanal and Small-Scale Mining in the Tarkwa Mining District of Ghana", *SME Annual Meeting*, Denver, CO, 4 pp.

Bogdanovic, D., Nikolic, D. and Ilic, I. (2012), "Mining Method Selection by Integrated AHP and PROMETHEE Method", *Anais da Academia Brasileira de Ciências*, Vol. 84, No. 1, pp. 219-233,

Bullivant, D. A. (1987), "Current Surface Mining Techniques", *Journal for the Transportation of Materials in Bulk: Bulk Handling*, Vol. 7, No. 6, pp. 827 – 833.

Dehghani, H., Siami, A. and Haghi, P. (2017), "A New Model for Mining Method Selection Based on Grey and TODIM Methods", *Journal of Mining and Environment*, Vol. 8, No. 1, pp. 1-17.

De Haan, J., Dales, K., McQuilken, J. (2020), "Mapping Artisanal and Small-Scale Mining to the Sustainable Development Goals", *Newark DE: University of Delaware (Minerals, Materials and Society Program in Partnership with Pact)*, 84 pp.

Donkor, A. K., Nartey, V. K., Bonzongo, J. C. and Adotey, D. K. (2006), "Artisanal Mining of Gold with Mercury in Ghana" *West African Journal of Applied Ecology*, Vol. 9, No. 1, 8 pp.

Dumakor-Dupey, N. K. and Bansah, K. J. (2017), "Environmental Issues of Artisanal and Small-Scale Mining in The Tarkwa Mining Area of Ghana", *SME Annual Meeting*, Denver, CO, 4 pp.

Dzigbodi-Adjimah, K. and Asamoah, D. (2010), "The Geology of the Gold Deposits of Prestea Gold Belt of Ghana", *Ghana Mining Journal*, Vol. 11, pp. 7-18.

Eshun, P. A. and Mireku-Gyimah, D. (2002), "Small-Scale Mining in the Tarkwa District: A Review of its Impacts", *7th International Symposium on Environmental Issues and Waste Management in Energy and Mineral Production*, Sardinia, Italy, pp. 877 – 884.

Eshun, P.A. (2005), "Sustainable Small-Scale Gold Mining in Ghana: Setting and Strategies for Sustainability", *Geological Society*, Special Publications, London, V. 250, pp. 61 - 72.

Foli, G., Agyemang, K., Brako, B.A., Gawu, S.K.Y. and Nude, P.M. (2020), "Characterisation of Alluvial Gold Exploration Data to Improve Gold Recovery in Ghana", *Arabian Journal of Geosciences*, Vol. 13, pp. 1-11.

Franks, D. M. (2020), "Reclaiming the Neglected Minerals of Development", *Extractive Industries and Society*, Vol. 1, pp. 1–8.

Fritz, M., McQuilken, J., Collins, N. and Weldegiorgis, F. (2018), "Global Trends in Artisanal and Small-Scale Mining (ASM): A Review of Key Numbers and Issues", *International Institute for Sustainable Development*, Winnipeg, MB, Canada.

Gupta, S. and Kumar, U. (2012), "An Analytical Hierarchy Process (AHP) Guided Decision Model for Underground Mining Method Selection", *International Journal of Mining, Reclamation and Environment*, Vol. 26, No. 4, pp. 324-336.

Guray, C., Celebi, N., Atalay, V. and Pasamehmetoglu, A. G. (2003), "Ore-age: A Hybrid System for Assisting and Teaching Mining Method Selection", *Expert Systems with Applications*, Vol. 24, pp. 261–271.

Hentschel, T., Hruschka, F., Priester, M. (2002), "Global Report on Artisanal and Small-Scale Mining", *Mining, Minerals and Sustainable Development (MMSD) Project Report,* International Institute for Environment and Development (IIED), London, UK, pp. 3.

Hentschel, T., Hruschka, F. and Priester, M. (2003), *Artisanal and Small-Scale Mining: Challenges and Opportunities*, International Institute for Environment and Development (IIED) Publications, London, UK, 94 pp.

Hilson, G. (2003), *The Socio-Economic Impacts of Artisanal and Small-Scale Mining in Developing Countries*, Swets Publishers, Netherlands, pp. 1.

Hilson, G. and McQuilken, J. (2014), "Four Decades of Support for Artisanal and Small-Scale Mining in Sub-Saharan Africa: A Critical Review", *Extractive Industries and Society*, Vol. 1, No. 1, pp. 104-118.

Hilson, G. and Maconachie, R. (2017), Formalising Artisanal and Small-Scale Mining: Insights, Contestations and Clarifications, *Area*, Vol. 49, No. 4, pp. 443-451.

Kessey, K. D. and Arko, B (2013), "Small-Scale Gold Mining and Environmental Degradation, in Ghana: Issues of Mining Policy Implementation and Challenges", *Journal of Studies in Social Sciences*, Vol. 5, No. 1, pp. 12 – 30.

Liu, A. H., Dong, L., and Dong, L. J. (2010), "Optimisation Model of Unascertained Measurement for Underground Mining Method

Selection and its Application", *Journal of Central South University of Technology*, Vol. 17, No. 4, pp 744-749.
McQuilken, J. and Hilson, G. (2016), *Towards Inclusive Formalisation of ASM in Ghana: Background Research for an Action Dialogue*, International Institute of Environment and Development, IIED, London, pp. 1.
Nieto, A. (2011), "Key Deposit Indicators (KDI) and Key Mining Method Indicators (KMI) In Underground Mining Method Selection" *Transactions of the Society of Mining, Metallurgy, and Engineering*, Vol. 328, pp. 381-396.
Popovic, G., Dordevic, B. and Milanovic D. (2019), "Multiple Criteria Approach in the Mining Method Selection", *Industrija*, Vol. 47, No. 4, pp. 47 – 62.
Quaicoe, I. (2017), "Organising and Developing an ASM Mining Site", *Artisanal and Small-Scale Mining Handbook for Ghana*, Geological Survey of Denmark and Greenland, pp. 28 – 37.
Rupprecht, S. M. (2017), "Bench Mining Utilising Manual Labour and Mechanised Equipment-A Proposed Mining Method for Artisanal Small-Scale Mining in Central Africa", *Journal of the Southern African Institute of Mining and Metallurgy*, Vol. 117, No. 1, pp. 25 - 31.
Salati, L. K. (2015), "An Integrated Management Model for Artisanal and Small-Scale Gold Mining in Northern Nigeria", *Unpublished PhD Thesis*, University of Mines and Technology, Ghana, 155 pp.
Salati, L. K., Mireku-Gyimah, D. and Eshun, P. A. (2016), "An Integrated Management Model for Artisanal and Small-Scale Gold Mining in Northern Nigeria", *International Journal of Advance Research*, Vol. 4, No. 12, 23 pp.
Schwartz, F. W., Lee, S. and Darrah, T. H. (2021) "A Review of the Scope of Artisanal and Small-Scale Mining Worldwide, Poverty, and the Associated Health Impacts" *GeoHealth*, Vol. *5, No* 1, pp. 3 – 6.
Shariati, S., Yazdani-Chamzini, A. and Bashari, B. P. (2013), "Mining Method Selection by Using an Integrated Model", *International Research Journal of Applied and Basic Sciences*, Vol. 6, No. 2, pp. 199-214.
Tepkor, A. S. (2005), "Transforming Small Scale Mining into a Form of Sustainable Livelihood for the Communities", *Unpublished BSc Project Report*, University of Mines and Technology, Tarkwa, Ghana, p. 30.
Yalley, A. B. (2020), "Illegal Mining Operations on AngloGold Ashanti (AGA), Obuasi Mine's Concession – Challenges, Impacts and Strategies for Addressing Them", *Unpublished MPhil Thesis Report*, University of Mines and Technology, Tarkwa, Ghana, pp. 30 – 45.
Ye, H. and Liu, F. (2012), "Underground Mining Method Selecting System Based on Fuzzy Theory", *Advanced Materials Research*, Vol. 402, pp. 631-635.

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