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Water Pollution from Artisanal and Small-Scale Mining Operations: Setting the Stage for a Novel Remediation Technology

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Abstract

Water pollution resulting from Artisanal and small-scale mining (ASM) operations has been a major challenge for many governments and stakeholders over the years. The effluents from ASM operations are reported in multitudinous studies to be discharged into water bodies such as rivers, lakes, streams, lagoons leading to the heavy metals concentrations and high physio-chemical properties of such water bodies beyond acceptable limits. These pollutants are known to be the causes of the Minamata disease, cancer, brain disorders and damages and could even lead to deaths if bioconcentrations are high in the human body. Even-though various remediation techniques such as physical and chemical precipitation, ion-exchange, reverse osmosis, membrane filtration, electrochemical treatment, solvent extraction, and adsorption, have emerged, the huge nature of the polluted natural water bodies coupled with the continuous discharge of ASM effluents makes the application of such technologies economically unsustainable. This study establishes the different dimensions of water pollution spanning from the 2 categories of ASM operations and the need for future remediation technologies to thrive on these 2 dimensions of water pollution for sustainable implementation. Methods used include total analysis of water from 2 legal ASM site and 1 central processing plant in Ghana. In addition, there was a review of 21 studies published between 2014 to 2024 to ascertain the nature of illegal ASM water pollution, the pollutant levels and the success of any remediation technique implemented for cleaning the water. Results from the study indicated that the legal ASM operations employed a management system which is mainly based on "contained and recirculated" technique and the 3-pond purification method to manage effluents. However, the illegal ASM operations discharge their effluents directly into natural fresh water bodies resulting in heavy metals concentrations and high physio-chemical properties of the natural water bodies beyond the WHO standards for fresh natural water. Moreover, none of the studies could report on the successful implementation of any remediation technology on the polluted water bodies. This study therefore recommends that future remediation technologies should consider the different dimensions of the water pollution from the 2 categories of operations for sustainable implementation.

Keywords

Artisanal and Small-Scale Mining, Water Pollution, Remediation Technologies, Sustainability, 3-Pond Purification System

1. Introduction

The diversities and dynamisms in ASM have made it difficult to get a single globally accepted definition for the sector (De Haan et al., 2020). Various countries and organisations have based the concepts of their definitions on the sizes of operations, capital investments, techniques of operations, the number of workforces, concession sizes, reliability of operations, operations sustenance, management structure, output of the mine and legislative requirements (Eshun & Mireku-Gyimah, 2002; Hentschel et al., 2003; Salati et al., 2016). For instance, the United Nations (UN) definition is based on the capital investment, annual and daily output, annual sales, number of workforce and the life of mine whereas the World Bank Group definition is based on the poverty-driven nature, place of occurrence, levels of literacy of the miners and mining expertise (Dreschler, 2001; Aryee et al., 2003; Azubike, 2011; Bansah et al., 2016). In Ghana, the definition is based on the size of concession, capital investment and the number of workforce whereas China's definition of ASM is based on the annual production (Mallo, 2012; Bansah et al., 2016; Mutagwaba et al., 2018). The historical, economic, developmental, geological and social conditions of the sector in the various countries vary in numerous cases (Dreschler, 2001).

ASM is an important economic activity of which if account is taken off presents a host of positive attributes. The miners exploit a wide range of minerals and collectively produce significant quantities of minerals with production in some countries being equal to or more than production from the Large-scale mining (LSM) sector. ASM is noted to produce about 20% of the global gold production, over 90% of the global gemstones and over 80% of the global diamond production (Mutagwaba et al., 2018). Notably, ASM produces 75% of the bauxite in China and 100% of diamond in Ghana (Fritz et al., 2018; Mutagwaba et al., 2018). Moreover, minerals production from the sector in some countries has seen a tremendous increase over the years thereby boosting their economies. For instance, gold production from ASM in Ghana has seen a tremendous increase over the years (as shown in **Table 1**), thus accounting for Ghana overtaking South Africa in 2018 to become the leading producer of gold in Africa. Furthermore, construction materials such as sand and gravels are produced during the processing of the ore. Besides, employment generated from the sector presents the highest numbers in the mining industry accounting for about 90% of the total global gold mining employment (Gunson & Jian, 2001; Hruschka, 2015). The importance of this sector cannot be overemphasised as it is also an alternative for mining smaller deposits which otherwise would not have been economically viable mining using LSM techniques.

Table 1. Comparative gold production in Ghana: LSM versus ASM.

Year	Large Scale Producers (Oz)	Small Scale Producers (Oz)	Total Ghana Production (Oz)	Production Factor ASM to Total (%)
2000	2,168,802	145,662	2,314,464	6.3
2001	2,184,313	185,596	2,369,909	7.8
2002	2,075,954	160,879	2,236,833	7.2
2003	2,085,070	221,063	2,306,133	9.6
2004	1,783,400	246,570	2,029,970	12.1
2005	1,913,534	225,411	2,138,945	10.5
2006	2,095,553	247,063	2,342,616	10.5
2007	2,239,678	388,594	2,628,272	14.8
2008	2,378,012	418,943	2,796,955	15
2009	2,564,095	555,737	3,119,832	17.8
2010	2,624,391	767,196	3,391,587	22.6
2011	2,697,612	978,611	3,676,223	26.6
2012	2,842,585	1,481,670	4,324,225	34.3
2013	2,868,763	1,528,224	4,396,987	34.8
2014	2,960,583	1,510,990	4,471,573	33.79
2015	2,592,564	1,031,176	3,623,740	28.45
2016	2,576,489	1,283,791	3,860,281	33.26
2017	2,807,025	1,424,351	4,231,376	33.66
2018	2,813,913	2,130,155	4,944,069	43.1
2019	2,994,771	1,679,203	4,673,974	35.93
2020	2,830,041	1,264,029	4,094,070	30.88

(Source: Ghana Minerals Commission, 2021).

Despite the contributions of the sector towards economic growth, it is known to be a major source of environmental degradation (Afum & Owusu, 2016; Dossou Etui et al., 2024; Fonshiynwa et al., 2024; Opoku et al., 2024). Particularly of concern is the increasingly unmanageable state of water pollution resulting from ASM operations. The water pollution according to (Amegbey & Eshun, 2003) is caused when waste rocks and ASM tailings materials undergo oxidation in the process of Acid Mine Drainage (AMD) and thereby mobilise heavy metals into the environment. Some studies have found that direct discharge of ASM effluents and sediments into the water bodies namely streams, rivers, lakes and even the ocean to be the major cause of pollution of such water bodies (Fonshiynwa et al., 2024; Opoku et al., 2024). The effluents which are usually not treated are highly turbid and contain heavy metals such as Hg, As, Pb, Cd, Zn, Mn, Sn, Fe, Al, Cu, Cr and Ni (Amegbey & Eshun, 2003; Gafur et al., 2022; Fonshiynwa et al., 2024). The pollutants are generated during the excavation, transportation via various media and processing of the minerals. The impact of water pollution is highly felt when these water bodies are relied on for drinking, household usage and for industrial purposes without any prior treatment. In the urban areas, treatment of such polluted water bodies is becoming highly expensive and complex. Ghana's Water Company Limited (GWCL) reports of possible shutdown of 2 of its major treatment plants due to the extreme cost of water treatment resulting from the increasing turbidity of water bodies from ASM operations (Boakye, 2022). Moreover, the exposure and concentration of the heavy metals and chemicals in the human body leads to neurological damage, cancer, Minamata disease, cancer, brain disorders and damages and could lead to deaths if bioaccumulations are high (Bansah et al., 2016). There is therefore the urgent need for a sustainable remedy to be developed to prevent water pollution from ASM operations.

Many water treatment technologies have been developed over the years. These technologies have been classified as Active Treatment Technologies (ATT) and Passive Treatment Technologies (PTT). Methods considered as ATT include neutralisation, sulfate removal, electrochemical technologies, reverse osmosis and ion exchange. The methods considered as PTT include constructed wetlands, anoxic limestone drains (ALD), open limestone channels, permeable reactive barriers, phytotechnologies and biochemical reactors (Seervi et al., 2017; Abdelhamid et al., 2024). These technologies have been employed in many industries including the LSM for water treatment. However, there is yet to be a study that accounts for the use of any of the water treatment technology for the ASM industry. Moreover, the dimensions of water pollution from ASM are different dependent on the levels of regularisation. The legal operations employ the "contained and recirculated" technique and the 3-pond purification method (filtration method) whereas the illegal ASM operations discharge their effluents directly into natural water bodies. It is therefore important that future remediation technologies consider the different dimensions of water pollution from the 2 categories of operations for sustainable remediation.

This study is aimed at establishing the different dimensions of water pollution spanning from the 2 categories of ASM operations (legal and illegal operations) and thereby set the stage for future remediation technologies to thrive on these 2 dimensions of water pollution for the sustainable implementation of the technologies.

2. Materials and Methods

This study employed a hybrid method of field studies and complete analysis of water samples from registered ASM sites and a review of literature on water pollution from ASM operations. This was done to get the details of water pollution from both the regulated (legal) ASM operations and the non-regulated (illegal) ASM operations. The following sections detail the methods and materials used for the literature review and the field studies. The field studies targeted only the regulated ASM sites, because the illegal ASM sites at the time of the field studies (from January to February, 2024) exhibited violent tendencies which could put the researcher's life into danger. As such, the literature review was used to suffice for the field studies for the illegal ASM sites.

2.1. Materials and Methods Used for the Literature Review

Table 2. Selection criteria for the literature review.

Duration to be covered	Publications between 2014 and 2024
Publication Type	Peer-reviewed journals excluding literature review papers
Geographic regions covered	All geographic regions
Publication language	English
Accessibility of Publication	Open access
Keywords and Abstracts words	Artisanal and small-scale mining, small-scale mining, artisanal mining, artisanal and small-scale gold mining, small scale-gold mining, ASGM, illegal mining, ASM Water pollution, heavy metals concentration, pH, Turbidity, mercury, effluents, waste water, rivers, streams, water contamination, acidic water, water quality Analytic values, Atomic Absorption Spectrophotometer, AAS, Inductively coupled plasma optical emission spectroscopy, ICP-OES, water sampling, particle size distribution, heavy metals measurements, Inductively coupled plasma mass spectroscopy, ICP-MS Water treatment, remediation, passive treatment, active treatment, cleaning technology
Type and form of document	Empirical studies

(Source: Ghana Minerals Commission, 2021).

To access water pollution from ASM operations, mode of measurement of the pollution, the levels of pollution, and the remediation techniques employed, a search was conducted on 4 scientific databases namely, Scopus, Google Scholar, ResearchGate and Academia in August 2024 to identify peer-reviewed journals on the subject matter. The duration of the publications was limited between 2014 and 2024 in order to get recent information on the subject matter. The search resulted in the identification of 54 peer-reviewed journals relevant to the subject matter excluding literature review papers. The selected papers were further screened to exclude studies which focused on water pollution from industrialisation, only soil tests studies, water quality tests in communities housing both LSM and ASM, studies that measured the bioaccumulation factor of some plants in ASM sites and studies that measured the vulnerability of males, females and children to heavy metals pollution and concentration. A total of 21 quantitative studies were finally selected for the literature review using the selection criteria shown in **Table 2**. The tables and figures for the literature review were generated using Microsoft Excel. The themes for the literature review focused on the authors, the year of publication, the country where the study was conducted, the journal of publication, the aim of the study, study methodology, results and remediation technique employed or recommended.

2.2. Materials and Methods Used for the Field Studies and Analysis

The field work was concentrated in 2 geographic areas, Tarkwa and Prestea in the Tarkwa-Nsuaem and Prestea-Huni Valley Municipal Districts of Ghana, respectively. These mineral-rich districts were chosen because of their long history of gold mining operations (both LSM and ASM), high numbers of ASM operations and the potentials of these mineral-rich districts to continue to host more ASM operations for several centuries to come. According to (Dzigbodi-Adjimah & Asamoah, 2010), Tarkwa and Prestea districts are respectively the second and third largest producers of gold in West Africa after Obuasi. An indication that this research will have higher impact as ASM mining in these 2 districts are likely to exist for many years to come. Moreover, these 2 areas fall under 2 prominent geological groups in Ghana, that is the Birimian Supergroup for Prestea and the Tarkwaian Group for Tarkwa. A purposive sampling of the mining sites was done to represent the different types of gold deposits exploited for ASM operations, that is alluvial, colluvial and hard rocks and to represent the different forms of effluents from different ASM operations (that is underground, surface and the central processing plants). A total of 2 mining sites, 1 hard rock underground mine in Tarkwa, 1 alluvial and colluvial surface mine in Prestea and 1 hard rock central processing plant in Prestea were chosen for this study.

2.3. Information about Study Areas

2.3.1. Prestea

The field work was concentrated in 2 geographic areas, Tarkwa and Prestea in the Tarkwa-Nsuaem and Prestea-Huni Valley Municipal Districts of Ghana, respectively. Prestea is a town with a long history of gold mining dating back to the late 1800s during the British colonial rule. The town 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 has a tropical wet and dry (savanna) climate. The district's yearly average temperature is 27.44˚C (81.39˚F) which is −1.42% lower than Ghana's averages. Prestea typically receives about 126.73 mm (4.99 inches) of precipitation and has 278.76 rainy days (76.37% of the time) annually. The town is within the rainforest bioclimatic zone of Ghana (Dzigbodi-Adjimah & Asamoah, 2010). Gold deposits in Prestea are made up of Quartz Vein Type (QVT) and the Disseminated Sulphide Type (DST). According to (Dzigbodi-Adjimah & Asamoah, 2010), the QVT orebodies are generally of higher gold grades and lie within a graphitic gouge in the fissure zones whereas the DST are mostly located in sheared or crushed rocks near the fissure zones.

2.3.2. Tarkwa

The Tarkwa town is located on latitude 5˚18'23.18" N and longitude: −1˚59'5.06" W. The town has a long history of mining operations together with other allied mining businesses. Tarkwa is located within the rainfall belt and has evergreen equatorial vegetation. Trees range in heights from 15 to 40 m and have broad crowns. Local geology of the Tarkwa is basically made up 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 (Bansah et al., 2016).

2.4. Information About the Mining Sites

2.4.1. Alluvial and Colluvial ASM Site in Prestea

The alluvial and colluvial 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 5˚20'30" N - 5˚20'42" N and longitudes 2˚09'21" W - 2˚09'30" W. It 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 the acquisition of the mineral right in 2014.

The area is made up of slopes in the northern direction towards the Ankobra river and a series of northeast-southwest trending sub-parallel ridges, about 2 km wide in the eastern part of the project area. These ridges range in height from 150 m to 195 m with lower hills ranging from 70 m to 110 m (Perrouty et al., 2012). The lithology of the block comprises of dark grey to black well-foliated graphitic phyllite, interbedded greywacke, which is medium grained and silicified, and sporadic occurrence of conglomeratic textures with poorly sorted sub-angular to angular quartz pebbles in a lithic sediments matrix, some mafic intrusive (basalt) and the highly weathered and altered yellow to dark grey granite. Gold mineralisation is of 3 major types: reef vein or lode deposits, auriferous quartz-pebble conglomerates (colluvial deposits) and recent placer gold deposits (alluvial deposits) (Perrouty et al., 2012). **Figure 1(a)** and **Figure 1(b)** shows the various ore deposit types found on the Bazuri concession.

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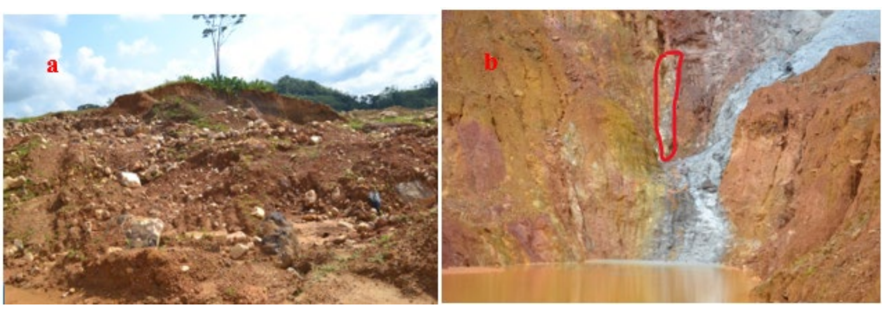

Figure 1. (a) Image of alluvial and colluvial deposits at the mine; (b) Image of vein deposits (highlighted red) at the mine.

Mining and Mineral Processing Methods Employed at the Mine

The mine employs surface mining technology to mine the alluvial, colluvial and vein deposits. Precisely, it employs the open pit mining method to mine the ore deposit. Even though, some exploration works such as trenching and a few diamond drilling had been done, the information was too scanty to define the mineral resource. The mine was actively operating a single pit which had a single bench of height of about 30 m high. The high wall and the soft nature of the alluvial materials being mined caused the materials to be reeling down making the operational pit unsafe. There were neither benches nor safety berms installed within the 30 m deep pit. There was a single haulage ramp which led to the pit. Due to the absence of a geological block model, there were no mine designs and plans to guide the mining process.

The mine employed direct excavation and loading of materials without any drilling and blasting operations due to the soft nature of the alluvial materials that were being mined. Materials handling was achieved by means of a shovel-truck system, precisely by the use of backhoe excavators and haulage trucks. The mine operated 2 excavators, with one used for loading materials into the crusher and the other used for excavation and loading of materials within the pit unto the single truck hired by the mine. Occasionally, the mine hired dozers and graders to clean the pit floors, push materials and clean the haul roads.

Ore processing was done by the use of 2 crushers and a hammer mill. The mined-out ore gravels were loaded with the excavator into the crushers to be crushed before being loaded into the ball mill to be milled and washed. However, the alluvial materials are loaded directly into the ball mill and washed after milling. The ball mill is installed with mesh carpets which trap the gold due to the denser nature of the gold. The trapped gold is then washed and smelted using the direct smelting method. There is also a shaking table employed as a gravity separator. Gold occurrence at the mine are mostly fines with few nuggets. Figure 2(a)-(d) shows the open pit, the excavator used at the mine, ball mill and the shaking table respectively.

Figure 2. (a) Open Pit at the Mine; (b) Excavators used at the Mine; (c) Hammer Mill used at the Mine; (d) Shaking Table used at the Mine.

2.4.3. Central Hard Rock Processing Plant in Prestea

The central processing plant is located in the Prestea township and it serves as the central point for miners to transport their hard rock ore for processing. The hard rock gold ores mined require some crushing and milling, which majority of the ASM operations cannot afford on their sites. As a result, the miners transport their rocks from far and near sites to be processed for them. The ore is first crushed using the local hammer mill and then milled using the locally produced disk mill.

During the field visits, it was observed that dry milling of the ore resulted in the milling area being extremely dusty. However, the miners had no nose mask and safety goggles on to protect them from the dust. In addition, washing of the ore sludge on the sluice was done with their bare hands without hand gloves. This exposed their skin to harmful chemicals or heavy metals likely to be naturally occurring within the rock mass or generated during drilling and blasting. Figure 3(a) and Figure 3(b) shows the disc mill being used with dust around it and the washing of the ore on a sluice box by a miner.

Figure 3. (a) Disc Mill in use; (b) Washing of Ore on a Sluice Box.

2.4.4. Hard Rock ASM Underground Mine in Tarkwa

The hard rock ASM underground mine is located in the southern portion of the northeast to southwest trending mineralised hill in Tarkwa in the Tarkwa-Nsuaem Municipality in the Western Region of Ghana. The concession is approximately 11 cadastral blocks; equivalent to 22.23 acres. From the Tarkwa-Effuanta junction, the concession is accessed via a feeder road extending about 1 km southwest up the northeast-southwest trending hill. Outcrops of the mine are of the Banket Series rocks of the Tarkwaian formation. These metasedimentary rocks are made up of 3 alternating quartzites and conglomeratic layers dipping moderately at about 35˚. 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.

Mining Method and Mineral Processing Methods Employed

The mine employs inclined room and pillar mining method and cut and fill mining method to mine the ore deposits. The bedded rocks are inclined at an angle of about 35˚. Entries to the mine are through the main shaft which was at the lower part of the hill or the adit which was at the upper side of the hill. At the time of visit to the mine, there were rehabilitation works ongoing on the shaft, so access through the shaft was impossible. The cut and fill mining method was employed at the ore block closer to the shaft whereas the room and pillar was employed on the ore block closer to the adit. The mine employs cut and fill and room and pillar mining methods because the initial state owned mine which used to exploit the deposits there used to employ these mining methods.

It was observed during the underground visits that the dimensions of the rooms and pillars were not regular. Whereas some areas had wider rooms and narrower pillars, others had narrower rooms and wider pillars. Fragmentation of the rocks was mostly achieved through the use of chisels and hammers. However, in extreme cases of hard ground, fragmentation was achieved through drilling and blasting using hand-held jackhammers and explosives. Material handling was achieved by loading the fragmented ore with shovels into sacks and carrying on the backs of the miners out for processing. Figure 4(a) and Figure 4(b) the adit as an underground entry and the room and pillar mining method respectively.

Ore processing was achieved by first of all drying the rocks in the sun as the ore material is mostly wet due to the underground conditions. The dry materials are then crushed in the hammer mill and further grinded in the disc mill. The powdered material is then mixed with water to form a slurry before amalgamation and smelting is done. The mine had secluded area reserved for amalgamation and also ensured that mercury was contained and not released into the environment,

Figure 4. (a) An underground adit; (b) Room and pillar mining with timber supports.

2.5. Sampling Locations

A total of 9 samples were taken from the alluvial/colluvial mining site (3 samples), the central processing plant (2 samples) in Prestea and from the hard rock underground site (4 samples) in Tarkwa. These sampling sites were chosen to give a good representation of the different heavy metals and chemicals in the effluences of different ore deposits within different geological settings. It was observed on the field that the registered ASM sites contained their effluences and employed the 3-pond purification system to filter the water and reuse it. At the alluvial/colluvial site, samples (1A, 2A and 3A) were taken from the fresh water dam, from the pond 1 and from the pond 3 as shown in Figure 5. The dam serves as the main water supply for mining and processing operations, whereas the pond 1 is the first settling pond for the effluents from the sluice box and the pond 3 is the final settling pond. Water from the pond 3 is reused for the operations especially during the dry season when water supply from the fresh water dam is limited.

The sample 1A was taken as the control point whereas samples 2A and 3A were chosen to test the effectiveness of the 3-pond purification system. At the central processing plant, the fresh water sample (RAW) and the final settling pond sample (USED01) were collected as shown in Figure 6. At the hard rock underground site samples were taken from the underground water dam (UG01) that is water pumped from the underground excavations, from the sluice box (RUN01), from the pond 1 (RUN02) and the pond 3 (RUN03) as shown in Figure 7 in order to access the effectiveness of the 3-pond purification system.

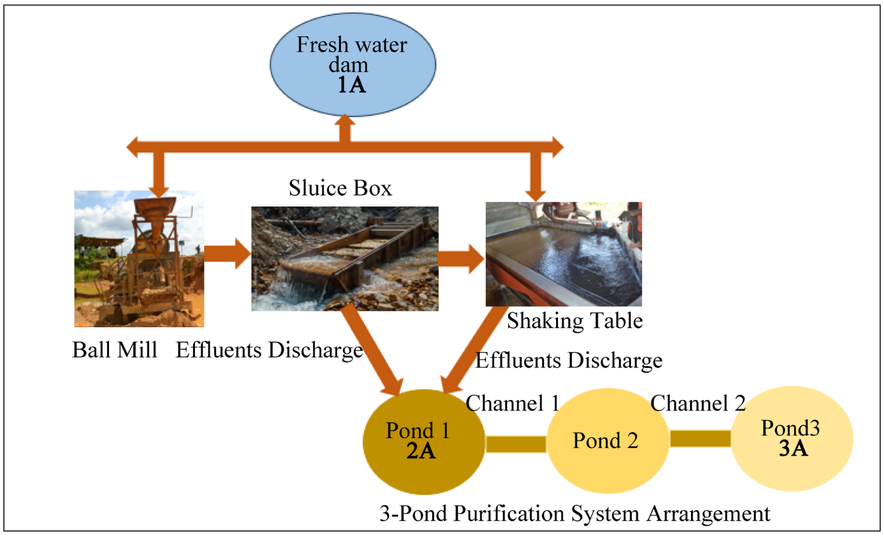

Figure 5. Schematic diagram of sampling locations at the alluvial/colluvial site in Prestea, Ghana.

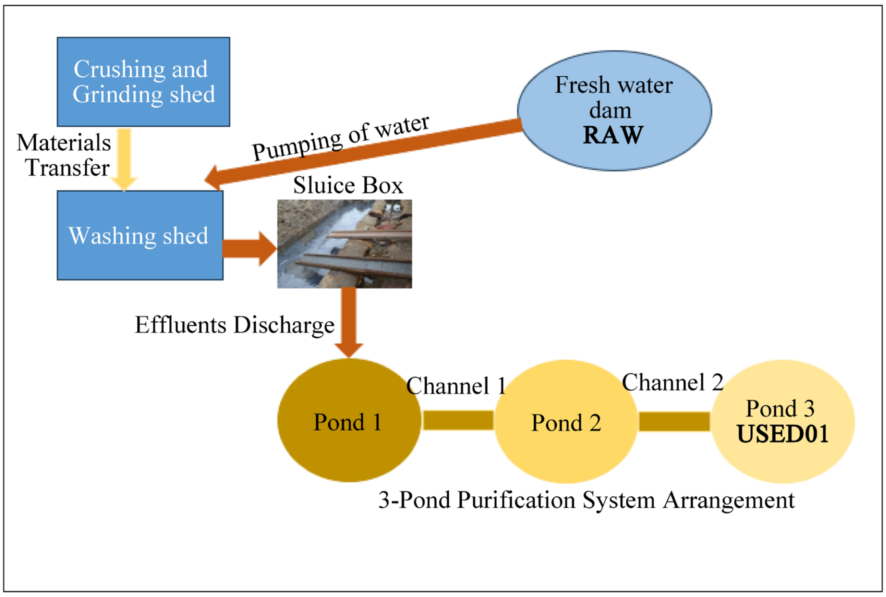

Figure 6. Schematic diagram of sampling locations at the central processing plant in Prestea, Ghana.

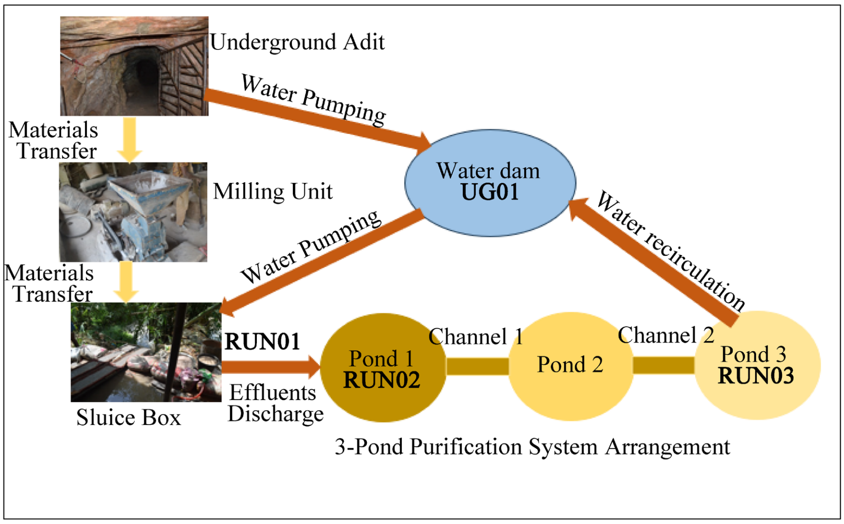

Figure 7. Schematic diagram of sampling locations at the hard rock underground site in Tarkwa, Ghana.

2.6. Sampling Techniques

Sampling of water in the ponds was done from January to February 2024 and was done opposite to the flow of water whereas sampling of water in the dams was done at about 0.5 m away from the sides of the dams. This was done to prevent excess silt from the ponds and dams which have settled from getting into the samples. The water samples were collected into a 1 L polyethylene bottle. At each sampling point, 3 samples (1 L each) were collected to be analysed for anions (1 L), cations (1 L) and 1 L for the pH, conductivity, total dissolved solids (TDS), total suspended solids (TSS), turbidity, total hardness, apparent colour, true colour, dissolved oxygen (DO), chemical oxygen demand (COD) and alkalinity.

The water samples which were intended for the cation (metals) analysis were preserved with 1.5 mL of 50% concentrated HNO_3 acid whereas the other 2 sample sets were not acidified. The samples were then kept in an iced-chest with ice packs at a temperature of 4˚C before being transported to the Environmental and Safety Laboratory of the University of Mines and Technology. In the laboratory, the samples were kept in the refrigerator and monitored at a temperature of 4˚C.

2.7. Analytical Techniques

The samples were analysed for the concentrations of Al, Ca, Cr, Cu, Pb, Cd, Ni, Hg, As, Mn, Na, K, Mg, Co, Zn and Se metals. Also, the concentrations of the following anions PO_4^{3-}, Cl^-, SO_4^{2-}, NO_3^-, NO_2^- and F^- were were analysed using the Ion Chromatography (IC) at the Environmental Monitoring Laboratory of University of Mines and Technology (UMaT), Ghana. Analysis of the metals concentration was achieved using the Atomic Absorption Spectrophotometer (AAS) at the same Laboratory. Quality-assurance measures for the AAS and the IC were done in accordance with the Ghana Environmental Protection Agency (EPA) 3050B standard. Calibration of the AAS was done using the sample 1A. An initial calibration verification was carried out at midpoints concentration to confirm the accuracy and precision of the instrument. After that, reverification of the calibration was done after every 1 hour of the instrument being in use. A blank solution of 100 mL deionized water and 1 mL concentrated HNO_3 was analysed for data reliability. Duplicate measurements were conducted for each of the sample with the results showing the mean/average with the accuracy level being ± 0.5%. Moreover, physico-chemical properties such as TDS, TSS, turbidity, total hardness, apparent colour, true colour, DO, Conductivity, pH and alkalinity were also analysed. Table 3 shows the parameters analysed from the water samples and the instruments used for the measurement.

Table 3. Selection criteria for the literature review.

Item No	Parameters	Instruments Used
1	Al, Ca, Cr, Cu, Pb, Cd, Ni, Hg, As, Mn, Na, K, Mg, Co, Zn, Se	Atomic Absorption Spectrophotometer (AAS)
2	PO_4^{3-}, Cl^-, SO_4^{2-}, NO^{3-}, NO^{2-} and F^-	Ion Chromatography (IC)
3	TDS	TDS meter
4	TSS, Turbidity	Turbidity meter
5	▪ Total hardness, True colour	Atomic Absorption Spectrophotometer (AAS)
6	Apparent colour	Colorimeter
7	DO	Dissolved Oxygen meter
8	Conductivity	Conductivity meter
9	Alkalinity and pH	PH Meter

3. Results and Discussions

Results from this study have been categorised into 2 sections, that is results from the literature review and results from the field studies. This was done in order to assess how the research methodology could influence the analytical results obtained for both the literature review and the field studies of the pollutants. It was also used to assess the different water pollution from the legal and illegal ASM operations. The results from the literature review represent the cases of the illegal operations and the results from the field studies represent the cases of the legal operations. The sections below explain into details the results obtained from the literature review and the results obtained from the field studies.

3.1. Results from Literature Review

A total of 21 journals published between 2014 and 2024 were selected for the literature review. The study focused on these years in order to get the most recent works done regarding the subject matter. In terms of the themes for the review, the study focused on the author (s), year of publication, the journal type, the country of the study, the aim of the research, the research methodology, results obtained and the remediation technology employed or suggested. It is important to note that the aim of the research is likely to affect the methodology to be used and subsequently affect the results obtained. For instance, a study that aims to assess the pollution level of ASM effluents may have a different methodology from a study that analyses the pollution levels of natural water bodies impacted from ASM operations and thus the results. Moreover, studies that only focus on certain pollutants were likely to have the results missing out on other pollutants. Table 4 below shows the details from the literature review.

Table 4. Results from the literature review.

No	References	Study Aims	Study Methodology	Results	Conclusions/ Recommended Remediation Technique
1	Boafo Brobbey et al. (2021)/ Ghana/Earth Sciences Malaysia (ESMY)	**1.** To assess the impacts of illegal small-scale mining activities on the water quality of the Aboabo stream in the Ahafo Region of Ghana. **2.** Determination of the bioaccumulation factor of Alchornea cordifolia, Chromolaena odorata and Spigella anthelmia growing within the stream.	**1.** Three (3) water samples and sediments samples were taken upstream, mid-stream and downstream of the Aboabo stream in the wet season and dry season. **2.** Plant species growing within the stream were accessed for the bioaccumulation factor. **3.** Analysis of As and Cd concentrations in the water and sediments were done using the Flame Atomic Absorption Spectrophotometer (FLAAS) whiles Hg analysed using Cold Vapour Atomic Absorption Spectrophotometer (CV-AAS). **4.** Bioaccumulation factor and translocation factor used for plants.	1. Heavy pollutions of Hg, Cd and As. **2.** Minimum values (mg/l): As - 0.815, Cd - 0.003, Hg - 0.90. **3.** Maximum levels (mg/l): As - 35.91, Cd - 1.12 Hg - 106.46	**1.** Effluents from ASM operations should be diverted away from the stream. **2.** Waste rock dump-site should be suited far from the stream to prevent run-off water into the stream.
2	Gyamfi et al. (2019)/Ghana/ Elsevier, Groundwater for Sustainable Development	The study assessed the impacts of the artisanal mining activities on the water resources and soil in the community. Particularly groundwater and stream water samples were analysed for pollution levels.	**1.** Fourteen (14) water samples were taken from hand-dug wells (2 samples), springs (2 samples), springs (2 samples) and a stream (3 samples) in April (before the rainy season) and in November (after the rainy season). **2.** Mapping of the sampling points were done with the aid of a Geographic Position System (GPS). **3.** Sampling, transportation and storage of the water were done according to the standards (Alpha, 1995). Water quality was assessed using the ICP-OES analyzer to test for Fe, Pb, Zn, As, Cu, Mn, and Hg concentration. **4.** The measured concentrations of heavy metals were compared with the WHO standards for drinking water.	**1.** Concentrations of As, Fe, Mn in the stream in April higher than WHO standards. **2.** Concentrations of As and Fe higher than WHO standards in November. **3.** As maximum levels 0.21mg/l, Fe maximum levels 4.19mg/l, Mn maximum levels 5.31mg/l. **4.** All other measurements were below the WHO standards. **5.** Maximum concentrations were recorded during the dry seasons	**1.** The study suggested that ASM operations should be regulated to prevent water pollution.
3	Nunoo et al. (2022)/Ghana/ Heliyon	Assessment of the extent of pollution of the Pra, Offin and Oda river by measuring physio-chemical parameters of turbidity, colour, pH	**1.** A total of 18 water samples were taken from 5 samples each from Pra river, Oda river and Offin river and 2 boreholes along Offin and 1 borehole along Pra river. **2.** Sampling was done in May 2021. **3.** Sampling protocols were observed. **4.** Council for Scientific and Industrial	**1.** The turbidity, colour, mercury and iron from the river and water samples exceeded WHO or GS175-1 limit. **2.** The Pra river recorded the most alarming result of turbidity (2,010 to 2,745 NTU), colour (3,000 to 4,500 Hz), total	**1.** Regular assessment of water samples to check give advice on the suitability for drinking. **2.** There should be collaboration amongst the various stakeholders to preserve

		and content of selected metals.	Research Laboratory (CSIR) standard methods were used for the analysis. **5**. The analytical values were compared with the WHO and CSIR (GS-175-1) standards on potable water for human consumption.	suspended solutes (2240 to 2570 mg/l) and total dissolved solutes (97.80 - 99.60 mg/ l, excluding 319.00 to 25,440 mg/l). **3**. The Oda river had lowest recorded values due to the dormant illegal gold mining activities for 5 years.	the water sources.
4	Gerson et al. (2018)/ Senegal/ Elementa Science of the Anthropocene	Assessment of the total mercury and methylmercury contamination in 4 active ASGM villages and 1 non-ASGM village.	**1**. A total of 123 soil samples, 22 sediment samples, and 29 water samples were collected from Bantako, Kharahenna, Kolya, and Sabodala (active ASGM villages) and Saraya (non-active ASGM village). **2**. Water samples were taken from the rivers along the towns. **3**. Sampling was done with the aid of ARC-GIS. **4**. Samples were collected in May 2016 before and after the heavy monsoonal rains. **5**. Sampling protocols followed the EPA Method 1669. 6. Water analysis was carried out using ICP-MS.	**1**. The concentrations of Hg in the river water samples in all the villages exceeded the USEPA Hg standard of 12 ng/l for the protection against toxic levels of bioaccumulation in aquatic organisms, but were below the WHO standard for drinking water.	**1**. Results should be shared with miners to increase their awareness of the contamination being caused by the use of mercury in their operations. **2**. Miners should be educated to use less risk-intensive mining technologies that eliminate mercury and increase gold production.
5	Afum and Owusu (2016)/Ghana/ International Journal of Environmental Monitoring and Analysis	The study assessed the level of concentration of heavy metals in the Birim River of Ghana.	**1**. Heavy metals concentration were analysed in the dissolved, suspended mineral fractions and the sediments of the river. **2**. Twenty-two (22) water samples (including tributaries) were taken at the upper and lower sections along the Birim River. **3**. Sediment samples were also taken at the exact points where the water samples were taken. **4**. The suspended particles within the water samples were filtered and assessed for heavy metals levels. **5**. Samples were analysed for metal concentrations of Cr, Fe, Ni, Zn, As, Cd, Hg and Pb using the Atomic Absorption Spectrophotometer (AAS), and the Inductively Coupled Plasma-Mass Spectrometer (ICP-MS).	**1**. The concentration of dissolved heavy metals in the water samples were below the WHO standards for natural fresh water except for Fe. **2**. The suspended particles and the sediments had higher metals concentrations. **3**. Nine (9) samples which were taken at locations having dominant ASM operations recorded higher metal concentrations showing the influence of ASM operations on water pollution.	1. Filtration of the water is required before domestic use.
6	Nukpezah et al. (2017)/Ghana/ West African Journal of Applied Ecology	The quality of water for irrigation from some selected sites along a river and a reservoir affected by ASM activities were assessed.	**1**. A total of 64 water samples were collected at the upstream, midstream and downstream of the river and from the reservoir for irrigation. **2**. Sampling was done between November 2015 to February 2016, that is the dry season where irrigation is required. **3**. The reservoir was selected as the control. **4**. The water samples were acid digested and assayed using Atomic Absorption Spectrophotometry (AAS).	**1**. Results obtained indicated that the turbidity, pH, conductivity, TDS and heavy metals particularly Pb and Hg were higher at the river sites compared to the reservoir. **2**. Majority of the measured parameters were within the range of the Food and Agriculture Organisation (FAO) limit for irrigation water quality except Hg, Cd, K and turbidity levels which exceeded the FAO permissible limits. **3**. It was inferred that ASM	1. The study warned the Municipality restrict the influx of ASM miners, as increase in their numbers could negatively impact the water quality.

				activities along the river affects the quality of the water.	
7	Yahaya et al. (2022)/ Nigeria/Diyala Agricultural Sciences Journal	The study evaluated the concentrations of Fe, Pb, Cd, Zn, Ni and Cr in the ore processing water and well-water in some selected villages of Anka in Nigeria.	**1.** A total of 16 sampling sites were identified with 3 water samples taken from each site, that is from the processing sites and from the well water. **2.** Water samples from the wells were used as the control. **3.** The water samples were acid digested and analysis carried out using the Atomic Absorption Spectrophotometry (AAS).	**1.** Results obtained indicated the presence of Fe, Pb, and Cd in all the water samples. **2.** The heavy metals Zn, Ni, and Cr were not detected in all the water samples. **3.** It was observed that the detected metals were beyond the WHO, USEPA, and EPA-EUC permissible limits but the exact standard was not stated. **4.** It was observed that the concentrations of Fe, Pb and Cd in the processing water exceeded that of the well water.	**1.** The study recommended periodic monitoring to be done in the area to assist government and other policy makers in decision making.
8	Agyarko and Dartey (2014)/Ghana/ Current World Environment	The study measured the concentrations Cd, Pb, Fe, Zn, Mn, Cu, Hg and As in water and sediments from 2 river courses (rivers Bonte and Gyeni) along 4 ASM localities in the Amansie West District of Ghana.	**1.** Five (5) water and sediment samples were randomly taken at five different points at each of the 4 localities (Esaase, Tetrem, Gyeninso and Adobewora). **2.** Water and sediment samples from the source of the rivers which had no record of ASM activities were taken to serve as the control. **3.** Sampling was done between May 2011 and July 2011, that is in the et season. **4.** Sampling was done to conform to the standard procedure described by DWAF (1992). **5.** Samples were acid digested and analysis carried out using the AAS. **6.** The analytical values obtained were compared to the WHO standards for drinking water and were assessed using the Geo-accumulation Index (Igeo) assessment and the Enrichment Factor (EF).	**1.** The results obtained indicated that the concentrations of Cd, Pb, Hg and As in water in the 4 ASM communities were beyond the WHO standards for drinking water. **2.** The sediments were found to be polluted to different degrees with Cu, Hg and As using the Geo-accumulation index. **3.** The Enrichment Factor indicated human influence-artisanal mining activities on the sediment concentration of Cd and Pb.	
9	Awuah et al. (2020)/Ghana/ Ocean Life	The study measured the levels of As, Hg, and Pb in water, sediment and fish from the Ankobra and Tano Rivers in Ghana affected by ASM activities.	**1.** The AAS was used to determine the concentrations of AS, Hg and Pb in water (30 samples), sediment (25) and fish (53 samples) in the Ankobra and Tano river. **2.** sampling of the fish was done randomly by picking fishes from 6 fishermen contracted to set fish traps overnight at the lower, middle and upper sections of the Ankobra and Tano rivers. **3.** Sediments were collected from each location using Ekman grab onboard a local canoe. **4.**Water samples were also collected from the sub-surface of the same area in the two rivers. **5.** The sampling dates and duration were not stated.	**1.**The concentrations of Hg, As and Pb were high in all analyzed areas. **2.** Results obtained indicated higher concentrations of Hg and As with highest concentrations in the fishes, followed by the sediments and lastly the water samples. **3.** Concentrations of Pb were highest in sediments, followed by the water samples and lastly the fishes. **4.** The concentrations of the metals Hg, As and Pb in the Ankobra river were almost the same as in the Tano river. **5.** The Hg and As levels in the	

			6. The analytical values obtained were compared to the WHO limits for freshwater habitats.	Tano and Ankobra rivers exceed the WHO limits for freshwater habitats.	
10	Tatah et al. (2020)/ Nigeria/Trends in Applied Sciences Research	The study evaluated the levels of heavy metals in water and soil samples from Mambilla artisanal mining site and its environs in Nigeria.	**1.** Eight (8) water samples were randomly collected from the mining site and its environs. **2.** Eight (8) different soil samples were collected in duplicates from the Nguroje town. **3.** Both the water samples and the soil samples were acid digested before analysis was carried out. **4.** Analysis of the concentrations of Pb, Hg, Cd, As, Fe, Cr and Zn were carried out using an energy dispersive X-ray Fluorescence Spectrometer. **5.** The results obtained for the heavy metals in the water samples were compared to that obtained for the soil samples (using the soil samples as control). The analytical values obtained were not compared to any known international standard.	**1.** The concentrations of Hg, As, Cd, Fe, Cr and Zn in the water samples collected at the mining site were significantly higher than in the soil samples.	
11	Obiri et al. (2016)/Ghana/ International Journal of Environmental Research and Public Health	The study assessed the physio-chemical content such as turbidity, TDS, pH and conductivity and the heavy metals concentrations in 70 water samples and 30 sediment samples in surface water bodies in Prestea, Ghana.	**1.** The random sampling technique was used to collect samples from nine rivers in the town which are affected by ASM operations. **2.** The samples were collected monthly between January and May 2011. **3.** A total of 70 water samples and sediment samples were collected from the sampling sites. **4.** The water samples were collected in 1.5 L bottles and acid digested before analysis was done. **5.** Analysis of As, Pb, Cd and Cd in the samples was done using the AAS.	**1.** The concentrations of As, Hg, Pb and Cd in the water and sediment samples were found to exceed the GS 175/1-WHO recommended guideline values, except for Cd in Rivers Dinyame and Mansi which were found to be below the limits. **2.** The pH and turbidity were found to be above the GS 175/1-WHO limits whereas the TDS was below the limit. **3.** The concentrations of As, Hg, Pb and Cd in the sediments were below the GS 175/1-WHO limits.	
12	Opoku et al. (2024)/Ghana/ Health Sciences Investigations Journal	The study assessed the concentrations of Hg, Pb, Cr, Co, Mn, Zn, As, Cd, Cu, Ni, Fe in water, soil, food and vegetation in communities where ASM activities have been halted for several years to establish the long-term effect of ASM.	**1.** Six to 10 soil samples were collected from 5 sampling point. **2.** Water samples were collected from 3 sources the river, the borehole water and the bottled and sachet water. **3.** The samples were acid digested before analysing the metal concentrations with the ICP-MS.	**1.** The concentrations of Hg, Pb, Cr, Co, Mn, Zn, As, Cd, Cu, Ni, Fe in water were generally lower than that of the soil, vegetation and food. **2.** Mn and Fe had the highest concentrations in water with the highest value of Fe (above the WHO standards for drinking water) recorded in the river samples. **3.** The heavy metals concentrations in the soil samples were generally high with Cr showing the highest values.	**1.** It is recommended that proper restoration of mined-out sites be done to reduce health and safety risks and protect lives in Ghana.
13	González-Merizalde et al. (2016)/ Ecuador/ Springer	The study assessed the levels of Hg and Mn in n several rivers of the	**1.** Water samples were collected from several streams and rivers of the Nangaritza River basin. **2.** Sampling of the river was done in 2	**1.** High Mn levels were recorded in river water and sediments in the highly contam-inated and moderately	

		Nangaritza River basin and the exposure in school-aged children living in mining communities near Nangaritza River basin, Ecuador.	upstream sides to the mining areas and the effluents from the mining sites. **3.** Three replicate sediment samples were collected at the same locations of the water samples. **4.** The analysis of Mn in the water and sediment solutions were done using the Flame Atomic Absorption Spectrometry (FAAS) and the Hg concentrations were analysed using the AAS.	contaminated areas closer to the ASM operations. **2.** The Hg concentrations were below the detection limit.	
14	Torrance et al. (2021) /Colombia/ Springer	To investigate the concentrations of Zn, Pb, Cu, Cd, As, Ni, Co, Sb and Hg of streams near Marmato in Colombia which are affected by ASM operations and ore processing.	**1.** Water samples were collected from 20 sampling sites in streams based on their proximity to mining operations in January 2012. **2.** The locations of the water samples were determined using the Garmin Model Oregon 450 global positioning unit. **3.** Parameters such as the temperature, pH, conductivity, oxygen reduction potential (ORP) and alkalinity were measured at the sampling points. **4.** Total metals concentrations were measured using the ICP-MS whereas the anions were analysed using Ion Chromatography Instrument.	**1.** The average concentrations of Zn, Pb, Cu, Cd, As, Ni, Co, Sb and Hg were beyond the WHO limits for drinking water.	**1.** It was recommended that improved mining operations operating under a robust permitting regime with appropriate environmental controls be adopted to ensure water quality.
15	Fonshiynwa et al. (2024)/ Cameroon/ Springer GeoJournal	The study assessed the quality of water from mining sites in Kambele and Pater in Cameroon by analysing the concentrations of Hg, Pb, As and CN in the water samples.	**1.** A total of 18 water samples were collected from mining sites in Pater and Kambele. **2.** The water samples were particularly collected from point sources, abandoned mine sites, rivers, washing points and panning sites. **3.** The samples were acid digested and refrigerated. **4.** The concentrations of Hg, Pb, As and CN were analysed using the AAS.	**1.** The concentrations of Pb and Hg were found to exceed the European directives (2000) and the WHO (2011) limits for drinking water. **2.** The concentrations of As and CN were found to be below the European directives (2000) and the WHO (2011) limits for drinking water.	**1.** More environmentally friendly ore processing techniques particularly gravity-based methods such as jigs and shaking tables should be used. **2.** Enforce environmental protection policies.
16	Sayom et al. (2023)/ Cameroon/ Springer Water Air Soil Pollution	The study analysed the water quality and heavy metals concentration in the Lom River which is close to the ASM area of Bekao in Cameroon.	**1.** A total of 32 water samples were collected at 8 sampling sites which were 1 km apart along the Lom River. **2.** Sampling was done upstream and downstream during the rainy and dry season. **3.** The water samples were taken at 30 cm depth from the river. **4.** The samples meant for trace metals analysis were filtered and acid digested on the field whereas samples meant for physiochemical properties analysis were kept in their natural state. **5.** Analysis of the metals was carried out using the ICP-OES.	**1.** Results obtained indicated a decreasing concentration in the order from Fe, As, Pb, Cu, Cr and Ni. **2.** The average concentration of Pb, Ni, As, Fe, and Hg exceeded the maximum WHO limits. **3.** The Water Quality Index (WQI) showed that about 56.25% of samples were not safe for domestic use. **4.** The heavy Pollution Index (HPI), the Heavy Metal Evaluation Index (HMEI), and the Contamination Index (CI) showed high level of heavy metal pollution. **5.** The water samples were found to be acidic to neutral, very turbid and weakly mineralised.	**1.** The study recommended strict monitoring of the pollution to prevent further degradation and protect the natural water resources.

17	Budianta (2021) /Indonesia/ Springer Environmental Science and Pollution Research	The concentrations of Cu, Pb, Zn and Cd in sediment samples of the Tajum river in Indonesia were analysed to determine the impact that ASM operations close to the river had on the river	**1.** A total of 12 sediment samples were taken from the upstream and downstream of the Tajum river. **2.** A sediment sample was taken from the tailings pond of an ASM mine. **3.** The levels of Cu, Pb, Zn and Cd were measured using the ICP-OES. **4.** The levels and mobility of Cu, Pb, Zn and Cd in the sediment of the Tajum River were evaluated using the mobility factor.	**1.** Results obtained indicated that concentrations of Cu, Pb, Zn and Cd in the tailings sediments exceeded that of the river sediments. **2.** The highest metal concentrations were found in the middle which is close to ASM operations and tailings. **3.** Results indicated that the average concentration of the metals in the sediment samples exceeded the mean crust.	
18	Dorleku et al. (2018)/Ghana/ Springer Applied Water Science	The study analysed the heavy metals concentrations of groundwater in Lower Pra Basin of Ghana to assess the impacts of ASM operations in the communities.	**1.** A total of 130 samples were collected from 65 boreholes in 45 communities in the dry and wet seasons in 2012. **2.** The samples were acid digested and refrigerated. **3.** Analysis of Cu, Fe, Mn, Cd, Zn, Pb in the samples was done using the AAS. **4.** Microsoft excel 2007 and SPSS 17.0 were used for the statistical analysis. **5.** Analysis of Se and As concentrations were determined using a Hydride Generant attached to the AAS. **6.** Hg concentration was determined using AAS-cold vapour.	**1.** The analytical values obtained for Cu, Mn, Zn, Fe, Al and Se were below the expected levels for mining affected communities. **2.** The analytical values obtained for Hg, Pb, Cd, and As were high enough to lead to physiological or sensory problems if consumed as drinking water. **3.** The pH levels of the water in the wet and dry season exceeded the WHO limits for drinking water with about 92% and 84% samples respectively.	
19	Mapatac and Atega (2024) /Philippines/ Recoletos Multidisciplinary Research Journal	The study analysed the physicochemical properties and the heavy metals concentration along ASM gold mining sites in the waterways in Surigao City, Indonesia.	**1.** The pH, temperature, Eh and conductivity of the stream and well water was determined on the site using Temperature-compensated electrodes and meters. **2.** Water samples collected were acid digested and stored in the refrigerator.		
20	Elwaleed et al. (2024)/Sudan/ Sustainability 2024	The concentrations of Hg in tailings of ASM gold mining operations, soil, tap water and groundwater in Darmali area in Sudan were analysed.	**1.** A total of 35 soil samples consisting of 18 agricultural soil samples, 10 samples from residential areas, 6 samples from ASM tailings and 1 reference sample were collected. **2.** Sampling was done in January 2023. **3.** Soil samples were randomly collected at a depth of 0 - 15 cm to reflect a large geographic area. **4.** A total of 8 water samples were collected, 4 from tap water and 4 from ground water. **5.** The water samples were acid digested to a pH below 2. **6.** The soil samples were air-dried under room temperature and sieved with a 150 µm mesh. **7.** The samples were transported to Japan for the analysis. **8.** Analysis of Hg in water samples and soil samples were conducted using	**1.** The recorded Hg concentrations were varied with respect to the different areas. **2.** The residential areas had the least average Hg concentration of 0.044 mg/kg, followed by agricultural areas of 0.057 mg/kg and tailings of 9.6 mg/kg. **3.** All the recorded values exceeded the reference point values of 0.016 mg/kg. **4.** The recorded values were compared to the Canadian soil quality guidelines limit of 6.6 mg/kg of which values for the tailings exceeded it. **5.** The average Hg concentration in the groundwater and the river Nile water were consistent with a value of 0.26 µg/l. **6.** This was below the recording	**1.** It is recommended that Hg contamination be mitigated and the tailings be treated to avoid further contamination.

		Mercury Analyzer (MA-3000).	in the control point (0.27 µg/l) and below the WHO limit and Sudan set limit for drinking water.
21 Passarelli et al. (2024)/Ecuador/ Toxics 2024	The study analysed the concentration of Hg in water samples from aquifers in 6 provinces of Napo, Sucumbíos, Orellana, Pastaza, Morona Santiago, and Zamora Chinchipe of the Ecuadorian Amazon region which had ASM operations ongoing there.	**1.** Water samples were collected from domestic wells in hamlets or rural communities located near mining concessions. **2.** A total of 6 provinces namely Napo, Sucumbíos, Orellana, Pastaza, Morona Santiago, and Zamora Chinchipe were used for the study. **3.** The total number of samples used for the study was 75. **4.** Sampling was done between March 2022 to July 2022 during the rainy season. **5.** The samples were acid digested before the analysis was conducted. 6. The analysis of Hg in the water samples was carried out using the AAS.	**1.** Results indicated that the Hg concentrations in groundwater in all the provinces except Orellana were between 0.0007 mg/l and 0.0056 mg/l. **2.** In the Orellana province, there was no detection of Hg in the groundwater samples. **3.** The detected concentrations of Hg were below the 0.006mg/l Maximum Permissible Limit (MPL) set by the Ecuadorian regulation for water quality for human consumption.

3.1.1. Publications by Country

The 21 journals were analysed according to the countries in which the studies were conducted. It was shown that Ghana had the highest number of publications of 10 regarding water pollution. The other countries had either 1 or a maximum of 2 publications within the search years of 2014 to 2024 as shown in **Figure 8**. The highest recorded publications in Ghana may be an indication of high ASM water pollution problems in the country. Hence more scientists are being prompted to research into the subject matter.

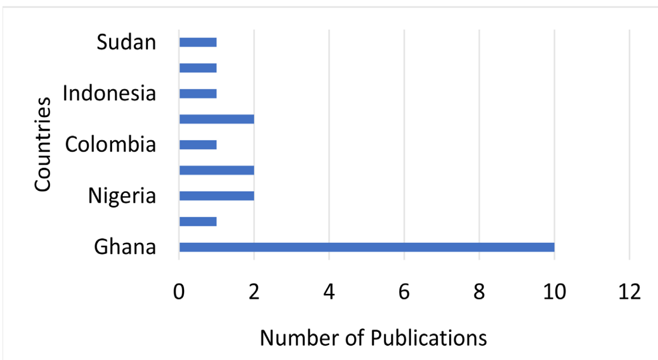

Figure 8. Number of ASM water pollution publications by country.

3.1.2. Publications by Years

The selected publications were analysed by the year of publication (**Figure 9**). The year that had the highest number of publications of 5 was 2024 with the years 2021 and 2016 having the second highest number of publications of 3 each. The increased number of publications in the year 2024 may be an indication of increased water pollution occurrences, hence more scientific research conducted in this subject area.

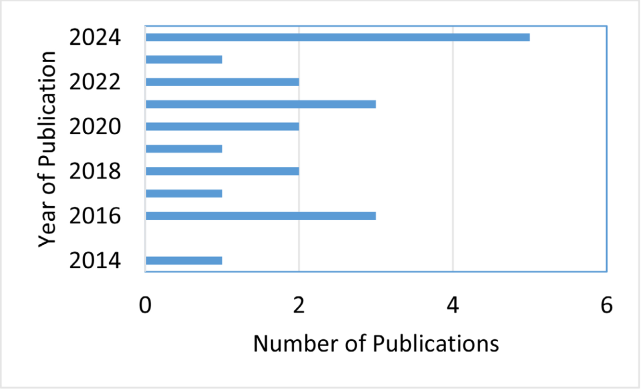

Figure 9. Number of ASM water pollution publications by years.

3.2. Results from Field Studies

The sections below explain the observations made and the results obtained from the field studies.

3.2.1. Contain and Reuse of Mine Effluents

At the mining sites, one key observation made was that the effluents from their operations were contained, filtered and reused. This is contrary to what is done at the illegal mining sites where the effluents are discharged directly into the natural water bodies without any prior treatment (González-Merizalde et al., 2016; Adewumi & Laniyan, 2023). The 3-pond purification system which was developed by (Amankwah, 2017) was being used to at the mining sites to contain the effluents and filter the water for further reuse.

3.2.2. Analytical Results

The results obtained from the complete analysis of the 9 water samples are shown in **Table 5**. These figures have been compared to the WHO (2011) Guidelines for Drinking-Water Quality and the Ghana Water Resources Commission (WRC) guidelines for natural surface water. It should be noted that the figures quoted on top of the results are the codes for the analytical protocols being used in the Laboratory. The highlighted figures (in red) indicate values higher than the WHO limits and the WRC limits.

Table 5. Water Analysis Results.

Analytical Parameters	Sample ID									WHO (2011) Drinking Water Guidelines
	1A	2A	3A	RAW	USED1	UG01	RUN01	RUN02	RUN03	
PH	7.53	5.67	5.22	6.64	6.44	6.75	7.29	6.84	6.8	6.5 - 9
Cond. (µS/cm)	76.2	63	85.8	1234	1265	337.7	650.5	570.9	574.6	200 - 800 µs/cm
TDS (ppm)	48.6	40.2	54.7	787.3	807.1	215.5	415	364.2	366.6	500 mg/L (500.57 ppm)
TSS (ppm)	23	57200	26	120	101	30	4460	3490	118	
TURB. (NTU)	17	51500	18	95	77	27	3220	2600	109	75 NTU

Continued

APP. Colour (Pt-Co)	199	10154	133	2650	1610	122	22350	13000	200	
True Colour (Pt-Co)	<1	<1	<1	<1	<1	<1	52	<1	25	
ALK. (ppm)	7	4.2	4.8	31.2	24.1	8.3	45.1	14.3	11.6	
Al-D (ppm)	<1	<1	<1	<1	<1	<1	<1	<1	<1	
Ca-D (ppm)	62.5	62.9	1	20.3	75.5	74.9	17.3	4.8	24.1	
Cr-D (ppm)	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.01 mg/L
Cu-D (ppm)	<0.002	<0.002	<0.002	0.0055	0.0055	0.0109	0.0655	0.0164	<0.002	2.0 mg/L
Pb-D (ppm)	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.1 mg/L
Cd-D (ppm)	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.1 mg/L
Ni-D (ppm)	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	0.5 mg/L
Hg-D (ppm)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.005 mg/L
As-D (ppm)	0.007	<0.001	0.003	0.067	0.031	0.001	0.004	0.003	0.001	0.1 mg/L
Mn-D (ppm)	0.6149	0.2084	0.7869	1.553	4.1646	1.1935	1.7721	0.334	0.4742	
Na-D (ppm)	8	7	10	100	48	21	100	80	80	
K-D (ppm)	1.8	3.9	3.3	20	20	2.1	16	10	10	
Mg-D (ppm)	3.61	0.14	1.23	27.34	23.06	3.15	2.06	2.04	2.37	
Co-D (ppm)	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	
Zn-D (ppm)	0.022	0.036	0.027	0.027	0.018	0.069	0.195	0.025	0.032	5 mg/L
Se-D (ppm)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
Total Hardness	170.9	157.6	7.5	163.2	283.4	200	51.7	20.4	69.9	
DO (mg/l)	4.48	4.53	4.32	3.65	4.08	4.38	3.27	3.85	4.17	500 mg/L
COD (mg/l)	54	421	63	87	133	34	337	289	175	
PO_4^{3-} (ppm)	0.44	0.11	0.19	0.25	0.15	0.08	0.22	0.14	<0.05	
Cl^- (ppm)	2.9	3.2	7	17	15.1	3.2	<0.5	<0.5	9.2	
SO_4^{2-} (ppm)	13	11	10	540	500	20	4.2	3.7	45	
NO_3^- (ppm)	1.88	2.52	2.45	122	11	35.4	1146.5	123	59.2	
NO_2^- (ppm)	<0.03	<0.03	<0.03	0.07	<0.03	0.8	9.9	7.2	10.7	
F^- (ppm)	<0.05	<0.05	<0.05	0.23	0.26	0.09	<0.05	<0.05	<0.05	

Note: 1 mg/L is approximately equal to 1 ppm.

4. Discussions

The following sections discuss the sampling techniques, results, standards of comparison of results of the literature review and the field studies. Also, the remediation technologies recommended by the various studies in the literature review have been discussed. It is worth noting that the research methodologies employed and the results clearly show that future remediation techniques will have to consider the different perspectives of ASM water pollutions (from legal and illegal) and find the best technique for each perspective.

4.1. Sampling Procedure

In assessing the sampling procedures used in literature, it was seen that many of the studies took the water samples from the natural water bodies whereas a few studies took the water samples from the illegal ASM effluents. It was not explained why many of the studies used samples from the natural water bodies as representation of ASM pollutant levels but it can be deduced that that the results obtained from such studies were not the true representation of the pollutant levels from the ASM operations. This is because the highly polluted smaller volumes of ASM effluents will be diluted by the higher volumes of natural fresh water thereby causing the analytical values of the pollutants to be reduced. A better approach to such studies should have been to collect both illegal ASM effluents and natural water bodies samples to ascertain the pollutants in both cases.

The field work conducted during this study, employed the right sampling procedure to give a true representation of the pollutant levels at the legal ASM sites. That is sampling involved the collection of the water samples from the various ponds. This sampling procedure was to aid in assessing both the pollutant levels and the efficiency of the 3-pond purification system in filtering the water.

The field studies gave a different narration of ASM water pollution other than the one reported in many studies. Whereas many studies report that ASM miners discharge their effluents in natural water bodies, it was observed that the legal operations selected for this study contained their effluents and reused them in their operations. Whereas, the illegal operations were the ones which discharged the effluents into the natural water bodies. It is important that researchers do not misrepresent the cases of the illegal and legal ASM operations in their researches. The legal ASM operations are regulated and monitored to ensure that as much as possible their operations do not lead to environmental degradation including water pollution. Researches which misrepresent the cases of the legal and illegal ASM operations give the wrong impression that all ASM operations degrade the environment, which is not so. Therefore, future remediation technologies should also consider the cases of the illegal and legal ASM operations and aim at finding solutions that best fit these 2 different cases.

4.2. Analytical Values

The maximum values recorded in literature were compared to the maximum values obtained from the field studies to ascertain the levels of pollution from the illegal sites and the legal sites. It is worth noting that apart from the fact that the legal operations contained their effluents, their operations are normally far away from natural water bodies. Therefore, ASM operations which are close to natural water bodies or which discharge their effluents into natural water bodies concluded to be illegal ASM operations. Table 6 shows the comparison between the maximum pollution values reported in literature (illegal ASM operations) and the pollution levels (mean values) from field studies (legal ASM operations) and the WHO (2011) Guidelines for Drinking-Water Quality limits and the Ghana Water Resources Commission (Water Resources Commission (WRC), 2018) guidelines for natural surface water.

From **Table 6**, it can be seen that the analytical values of turbidity, pH, TDS, conductivity, Hg, Pb, Fe, As, Ni and Cr recorded in literature (illegal ASM) were higher than both the WHO (2011) guidelines for drinking water quality and the WRC guidelines for natural surface water. Comparatively, only values recorded for turbidity, pH, TDS and conductivity for the field studies (legal ASM) were higher than the WHO limits and the WRC limits. The analytical values recorded for the heavy metals concentrations from the legal ASM sites in Ghana were relatively below the WHO standards and the WRC limits. This shows that the use of the 3-pond purification system on the legal ASM sites plays a role in lowering the pollutants levels in their effluents.

Table 6. Comparative analysis of maximum pollution levels field studies and literature.

Parameters	WHO Guidelines	WRC Guidelines	Literature Review (Illegal ASM)	Legal ASM Sites in Ghana
Turbidity (NTU)	75		4645	6407
PH	6.5 - 9	>0.5	8.47	6.58
TDS mg/L	500		3354	344.36
Conductivity µs/cm	200 - 800		1300	539.74
Hg mg/L	0.005	0.04	2.917	<0.001
Pb mg/L	0.1		1.64	<0.005
Cd mg/L	0.1	<0.1	0.04	<0.002
Cu mg/L	2.0	2.5	1.01	0.012
Fe mg/L	0.3	<0.1	432.9	
Zn mg/L	5	2	1.603	0.049
Al mg/L			736.9	<1.00
As mg/L	0.1	0.1	0.691	0.013
Mn mg/L			10.704	1.236
Co mg/L			0.517	<0.003
Ni mg/L	0.5	0-0.1	0.874	<0.003
V mg/L			3.378	
Cr mg/L	0.1	0.1	2.401	<0.005

Note: Values beyond the WHO limits have been highlighted red.

In Ghana, there are 3 water qualities set by governmental agencies to monitor water quality. The Ghana Standards Authority (GSA) has the Water Quality-Specification for drinking water (DGS 175) which sets permissible limits for chemical constituents in potable water. The Ghana Environmental Protection Agency (EPA) sets the guidelines for drinking water quality and the Ghana Water Resources Commission (WRC) sets the guidelines for water for domestic use quality and aquatic ecosystems or natural surface water quality. The GSA and the EPA water quality standards are similar to the WHO's guidelines. The WHO (2011) guidelines provide health-based benchmarks for chemical constituents in drinking water. However, the WRC standards have been set to take account of local water sources from surface or groundwater and contamination from mining and other industrial activities. Therefore, a comparison of the field data and the literature with the WHO guidelines and the WRC standards was made to assess the effluents qualities with national regulations and international health-based standards.

4.3. Standards for Comparison of Analytical Values

The standard for comparison of the analytical values is important as it depicts the extent of the pollution from the required value. It is important to note that the standard for the comparison of the analytical values should be in sync with the type of water being analysed. If the type of water being analysed is a drinking water or is used for domestic purposes, then the standard for comparison should be drinking water and if the water being analysed is natural fresh water, then the standard for comparison should be that of the natural fresh water or for aquatic ecosystems. This gives a true picture of the extent of pollution and the remediation technology that will be required to ensure that the required limits are obtained. Unfortunately, out of the 21 publications reviewed, none of the studies compared the analytical values with the right limit. Even though the studies were conducted on natural water bodies mainly streams and rivers with 6 conducted on ASM effluents, all the studies compared the analytical values to WHO guidelines for drinking water quality.

This is incorrect as it was not stated that the supposed water bodies were being drunk directly by the inhabitants of the communities or used for domestic purposes. The Ghana WRC indicated that if the supposed effluent is to be discharged into a water body which is used for domestic use, then the effluents quality should conform to standards for drinking water qualities. However, if the receiving water body is just a habitat for aquatic ecosystems, then the standards for natural surface water quality should be used for the effluents quality. The right method that should have been adopted by the researchers was to compare the analytical values obtained with the limits for natural fresh water bodies or drinking water quality upon justification that the receiving water bodies were for those purposes. Therefore, the standards for comparison of the water quality by the various studies do not depict as done in the true deviation of the pollutants from the set limits for water quality.

4.4. Recommended/Implemented Remediation Techniques from Literature

Out of the 21 journals reviewed, 11 journals gave recommendations on how to reduce pollution from ASM operations whereas the other 10 journals gave no recommendations at all. The recommendations given emphasised strict monitoring, strict environmental laws enforcement, education of miners on the pollution being caused by their operations and sharing of information on water pollution with miners and the communities. One (1) journal recommended that ASM effluents should not be discharged into the natural water bodies to avoid contamination. It was observed that none of these studies in the literature review had actually implemented a particular remediation technique on ASM effluences or on natural water bodies polluted from ASM operations. This indicates that there is still a gap in literature regarding the implementation of remediation technologies or the development of remediation technologies for ASM specific effluences or natural water bodies polluted from ASM operations.

4.5. Future Remediation Technologies

The results obtained from the field studies and that reported in literature clearly shows 2 dimensions of ASM water pollution. That is the legal ASM operations contain their effluents, filter it and reuse it whereas the illegal operations discharge their effluents directly into natural water bodies to pollute them. This discovery is contrary to what is reported in literature which claims that all ASM operations discharge their effluents without treatment directly into natural water bodies. Even though the various sites were chosen to represent the various deposit types exploited for ASM, it is worth noting that data from the 2 ASM sites and the central processing plant may not be enough to represent all legal ASM sites in Ghana. Therefore, future studies should consider increasing the number sites for the various deposit types to be more representative of the legal ASM sites.

The results from this study have inspired the authors to start working on developing an innovative technology for cleaning ASM polluted water having noticed the gap in knowledge in this subject area. The new technology will employ the use of natural waste materials such as sugar cane bagasse, coconut fibre, rice husk and rice straw for cleaning ASM effluents and assess the efficiency of these natural materials in adsorbing the pollutants from the effluents. The principle of operation of the new technology will be based on containing the ASM effluents and treating it with the natural waste materials (an active remediation technique). This approach will imply that lesser volumes of water will be treated at a relatively lower cost compared to the case of allowing effluents to be discharged into natural water bodies and spending much to treat the natural water bodies. It is therefore recommended that other researchers work at developing treatment technologies for ASM polluted water as there is a knowledge gap in this subject area.

5. Conclusion

This study analysed the water pollution from legal and illegal ASM sites in order to show the differences and the need for future remediation technologies to consider solutions for the 2 cases. The water pollution from the illegal mining sites were ascertained through literature review since the illegal miners were quite violent, thereby limiting field studies for the illegal ASM sites. Field visits were made to the legal ASM sites particularly 1 central processing site in Prestea, 1 alluvial/colluvial mining site in Prestea and 1 hard rock mining site in Tarkwa in Ghana. The mining methods and mineral processing methods of the selected sites were evaluated as these were likely to have an influence on the pollutants and pollution levels in their effluences. Tarkwa and Prestea (2 mining towns) in Ghana were chosen for the field studies because these towns have a long history of mining particularly ASM. The 3 sites were chosen to reflect the different geological terrains (Birimian and Tarkwaian) and also reflect the different geological deposits (hard rocks, alluvial and colluvial) mostly exploited for ASM gold operations.

In analysing the water pollution in the illegal sites, it was observed that many of the studies in literature sampled water from the natural water bodies instead of sampling from the ASM effluences. This is likely to alter their analytical results since the large volumes of the natural water bodies are likely to dilute the effluences and reduce the pollution levels. Moreover, many of the literature compared the analytical results obtained to the WHO limits or other standards for drinking water instead of comparing them to the limits for natural water bodies. By using the wrong standards for comparison, these studies end up presenting the wrong deviations from the set limits. Also, none of the literature reported on the implementation of any remediation technology on an ASM polluted water and the efficiency of the employed technology. This clearly shows a gap in literature and the need for researchers to focus on the development of ASM specific water remediation techniques and implementation.

From the field studies, it was observed that because the legal ASM operations are regulated and monitored, they contain, filter and reuse their effluences using the 3-pond purification system. The analytical values showed relatively lower levels of pollutants in the legal ASM effluences as compared to the values reported in literature for the illegal ASM. It can be concluded that there is a difference in the water pollution from the illegal and legal ASM operations. Whereas the illegal miners discharge their effluences directly into the natural water bodies, the legal operations contain their effluences, filter and reuse it in their operations. Therefore, future remediation techniques should focus on the possibility of containing the effluences from the illegal sites and treating them as the volumes of the waste water will lower implying it will be less expensive and easier to treat. Also, future remediation techniques for the legal sites should focus on the reduction of heavy metals concentrations and other pollutants in their effluences which are contained.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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