IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT)
e-ISSN: 2319-2402, p- ISSN: 2319-2399. Volume 20, Issue 8 Ser. 1 (August 2026), PP 18-31
www.iosrjournals.org

Removal Of Total Arsenic In Mine Wastewater Using Ferric Sulphate [$Fe_2(So_4)_3$]

Isaac Sefa
Thesis Submitted To Department Of Environmental Science, Kwame Nkrumah University Of Science And Technology, In Partial Fulfilment Of The Requirement For The Award Of Master Of Science Degree.

Abstract
It is vital to understand the geochemistry of arsenic in tailings and wastewater dams after the extraction of gold-bearing ores in nature. As a result, the levels of arsenic in the tailings and wastewater dams were examined. Using ferric sulphate as a coagulant, the removal potentials of high As concentrations in wastewater dams were investigated. However, the findings revealed that As levels in the tailings were higher than those in the wastewater dams.
Furthermore, the results from coagulation experiments gave a clear evident that, ferric sulphate have a destructive potency on arsenic in wastewater. However, effectiveness based on arsenic removal was achieved to be 99.96%. Among all the ferric sulphate concentration doses, 70 ppm was seen to be best in terms of arsenic removal with no residual iron (Fe) in the waste. The results further confirmed that, ferric sulphate has colour reducing effect when a comparative analysis of colour of wastewater after application and colour before application was done. Approximately, 95.4% effectiveness based on decolourization was achieved. Thus, from the study, it can be drawn that, coagulation using ferric sulphate is one of the best practicable technology for removal of arsenic ion from wastewater. Also, it has a great potential of reducing colour of wastewater. This research further tells that, mining activities generate high concentration of arsenic into various environmental media. Thus, monitoring of water quality has to be conducted on frequent basis by the EPA to ensure that effluent discharges from mining companies into the environment are in compliance with their set standards. I recommendation, the EPA has to put into their requirements, all mining companies that pollute the environment especially waterbodies need to be treated before permit is issued for operationalization.

Date of Submission: 27-07-2026 Date of Acceptance: 07-08-2026

I. Introduction

Arsenic is a chemical element with the atomic number 33 and the symbol As. Arsenic is a metalloid, which means it belongs to a group of elements called metalloids. A metalloid is a chemical element that contains both metal and nonmetal characteristics. It commonly occurs in minerals in conjunction with sulfur and metals. It can also be present in the environment, natural waters, and living beings (Abraham et al., 2010).

It is frequently mobilized as a result of a combination of natural processes such as reactive weathering, biological activity, and volcanic emissions, as well as a variety of anthropogenic operations such as mining (Smedley and Kinniburgh, 2002). Arsenic is widely known as a poison due to all of its characteristics. Because it exists in four different oxidative states, arsenic has a complicated chemical activity. Arsenic species have varying degrees of toxicity depending on their oxidative state and prevalence in the environment.

For chemistry and environmental protection, it is critical to investigate arsenic species and their behavior in various samples, particularly in natural waterways and the environment. The goal of this study was to determine the levels of As in mining tailings and wastewater, as well as devise methods for extracting them from these wastes. Thus, in order to achieve improved standards, innovative processes for treating industrial wastewater or mine wastewater for removal of high concentrations of arsenic or reduction of its toxicity should be developed.

Absorption, precipitation, coagulation and flocculation, membrane filtration, and hybrid membrane processes are all examples of best practicable technologies. As a result, oxidation prior to coagulation is thought to be the best technology and simplest method for destroying high levels of arsenic in order to meet the maximum acceptable limit (Islam et al., 2004). The coagulation process is influenced by a variety of factors, including pH, coagulant dose and type, and mixing.

Arsenic is a hazardous element that is persistent and bioaccumulative. The current most stringent legislation from the Ghana Environmental Protection Agency (EPA) stipulates a maximum effluent release limit of 1.0 mg/L. This is owing to arsenic's toxicity as a metal, which necessitates monitoring and bringing its concentration to a permissible level before discharge.

Coagulants are used to remove arsenic from wastewater in a variety of ways. However, ferric sulphate has proven to be more important and desirable in terms of effectiveness, operational costs, and reliability. As a result, many wastewater treatment firms select ferric sulphate for As treatment, although determining the correct dose is difficult. As a result, different trials on dose of ferric sulphate coagulant which could work best without leaving iron residue were performed. This would help to expand on a commercialized plants or on bigger scale wastewater treatment system,

Problem Statement

Arsenic pollution of water sources in Ghana, Obuasi municipality due to mining activities has had a severe impact on the socioeconomic lives of residents in the adjacent villages (Actionaid, 2006). The major arsenic-bearing mineral arsenopyrite is found in significant concentrations in gold ores (Osea et al., 1995).

Despite construction of new tailing facilities by Anglo-gold Obuasi mine to store wastewater following gold processing, some environmental issues persist. In 2005, for example, a tailing dam failure at Kokoteasua was allegedly caused by unlawful galamsey activities. As a result, the downstream communities of Kokoteasua, Abompekrom, and Akamprom were contaminated

(Obuasi mine report, 2005). As a result, their drinking water was tainted, resulting in increased sickness and mortality among inhabitants as well as significant marine contamination.

Chronic exposure of humans and animals to high amounts of As has been linked to a variety of human health impacts, including skin cancer and other internal malignancies, cardiovascular disease, and neurological abnormalities (Todel et al., 1999; Milton et al., 2001; Elangovan & Chalakh, 2006). Because of the poisonous effects of As, strict rules have been enacted in the industrialized world, such as the toxicity characteristic leaching procedure (TCLP) test for arsenical waste stabilization prior to disposal (Davis 2001; US-EPA, 1989).

Another instance occurred in the Kwabenafoso stream, a catchment area along the Obuasi mine environment, where anthropogenic As pollution was discovered, with a significant concentration of the metal observed in soils linked with tailings (Antwi Agyei et al., 2009). Concerns have made it mandatory for major mining companies to establish internationally accepted environmental standards for managing environmental issues such as acceptable levels of As contamination, in addition to the enactment of stringent regulations to stabilize arsenical waste prior to disposal.

The International Standard Organization series on the environment (ISO 14001) was established, and the Obuasi mine was certified in November 2006 (Foli et al., 2010). However, in the poor world, most environmental groups of mining firms rely on pH to monitor trace metals by simply guaranteeing near-neutral levels. As a result, this approach is not the greatest for dealing with a metal like As (Key, 2005; Norris, 2005), and further research is needed to develop more specific strategies for As removal from heavily contaminated wastewater. Coagulation with ferric sulphate is one of the most common and successful techniques of eliminating As from wastewater.

However, the right dose for treating wastewater effectively without leaving a challenge to the environment is not established for the Obuasi tailings and wastewater.

Justification

Ghana's Environmental Protection Agency (EPA) has established compliance requirements for mine effluent discharge. The of effluent discharge for arsenic is limit of 1.0 mg/L. The quest is to find the most cost-effective solution for reducing arsenic concentrations in mine effluent from around 200 mg/L to the EPA's permissible level of 1.0 mg/L. To answer this question, researchers must explore and discover a viable solution for removing total arsenic from contaminated water.

As a result, employing ferric sulfate [$Fe_2(SO_4)_3$] to remove total arsenic from mine effluent is one of the most practical technologies available.

Main Objective

The major objective of this research was to assess the potential of the right dose of ferric sulphate in removing arsenic from wastewater.

Specific Objectives

- Determine the compositions of total arsenic levels in the tailings and wastewater dams.
- To assess the removal potentials of different concentrations of Ferric Sulphate [$Fe_2(SO_4)_3$] on total arsenic in the wastewater.

II. Literature Review

Introduction

This chapter discusses some of the research literatures that are pertinent to the topic. Not only does the chapter evaluate and analyze the relevant material, but it also compares and contrasts it. As a result, the literature evaluation identifies the gap in the existing literature that this study aims to fill. The review also identifies some of the literature's strengths and weaknesses, as well as providing objective interpretation of its findings. Thus, for clarity and convenience, the literature review is systematically and thematically structured.

The literature review begins with an overview of mining and development, including gold mining and development in Africa, the effects of gold mining on water bodies, arsenic concentration in mine effluent, arsenic usage, arsenic ecotoxicology, and arsenic species in water and many others. It goes on to discuss several arsenic destruction technologies as well as other potential arsenic removal methods.

Mining and development

In many developing countries around the world, the mining sector has seen considerable expansion (Bebbington et al, 2008). This generates tax and revenue, as well as jobs and a better standard of living in a country. Ghana has been producing gold since the fifteenth century (Winfried, 2001). As a result, the mining industry has been a significant element of the economy, with gold accounting for almost 90% of the total (Aryee, 2012). Ghana is Africa's second-largest gold producer and the world's ninth-largest gold producer (Aryee, 2012). Mining employs over a million people in the country, whether on a major or small scale.

Apart from providing employment to a significant segment of the people, gold export profits and foreign exchange earnings total many millions of cedis. Ghana produced 3.6 billion ounces of gold in 2011, the biggest amount the country has ever produced. As a result, export sales of almost $5 billion were generated, with the small-scale industry accounting for 28 percent of overall production in 2011 (Aryee,2012). In 2011, the sector directly contributed 38.3% of Ghana's total corporate tax earnings, 27% of government revenue, and 6% of GDP. About 90% of all gold produced in the country comes from large-scale operations, with the other 10% coming from small-scale miners known as galamsey operators (Aryee, 2002).

As various authors have attempted to explain how mining leads to development in many countries and has become an outlet for investment, there has been a rising dispute about whether the concepts of mining and development are quite associated. Leading development theories and their normative assertions with respect to mining are built on the work of landmark ideas within the sector, according to scholars such as Graulau (2008). His thesis is that development theories have a tumultuous relationship with the topic of mining, swinging back and forth like a pendulum with the question 'Is mining good for development?'

Mining for development is often supported by ideas that embody a high-quality perspective of capitalism within the classical political economic system heritage and mainstream development economics. Mining is a major stumbling block to growth. This is because it has a significant impact on the agriculture sector of the economy (Owusu, 2016). As a result, it is thought that agriculture is the backbone of a country's development, and that if it is hampered, it would have an impact on all other developing sectors (Owusu, 2016).

Spiegel (2015), who critically examines the implications of the Minamata convention for the artisanal mining zone in Sub-Saharan Africa, which currently relies on mercury amalgamation for gold extraction, has conducted a critical analysis based on examples from Zimbabwe and Tanzania, two countries with divergent political challenges but expanding artisanal mining sectors. They suggest that a paradigm shift is required to address the linked technological, political, and socioeconomic issues that marginalized mining populations face.

In addition, according to Akpalu and Normanyo (2017), in order to attract a wider range of foreign direct investment into their gold-mining sectors, many mineral-rich countries in Sub-Saharan Africa have been willing to overlook serious instances of mining company non-compliance with environmental requirements. Where regulatory oversight and enforcement failures have resulted in excessive levels of pollution in many mining areas.

Gold mining and development in Africa

According to Gennady and Volodymyr (2017), the material is divided into three separate but thematically united elements that describe the phenomenon of gold rush-spontaneous big-scale gold mining at newly discovered deposits in remote (for Europeans) parts of the world in the second half of the nineteenth century.

Rural poverty remains prevalent in Mozambique, according to Dondeyne and Ndunguru (2014), despite the country's abundant natural resources and strong economic growth. Finding ways to convert this money into development opportunities is the task. In contrast, artisanal gold mining is the most direct source of income for many rural people in central Mozambique, and it is likely to stay so. They remark on the future of artisanal gold mining in Mozambique, based on personal experiences.

Impact of Gold mining on natural resources

Many people's livelihoods have flourished as a result of gold mining, whether large or small-scale, such as galamsey. It has improved the economic and job situation, as well as drawing attention to the impact of gold mining on the environment and how to control these effects on living species. Gold mining has an impact on almost every aspect of the ecosystem, but the physical impact on water and aquatic life is the most significant. As a result, when discussing the impact of gold mining on water bodies, all of the focus shifts to individuals involved in small-scale activities like galamsey. This is due to the fact that the latter is casual, generic, frequently unmonitored, and unrestrained. Concerns have been raised that not only small-scale mining has an influence on water resources; large-scale mining enterprises with operating licenses also degrade our natural resources more than is necessary.

Land degradation, depletion of forest and water resources, and air pollution are all examples of these effects. Other than agricultural and wildlife production, land released for mining is a form of productivity disruption. However, this has an impact on food security and GDP, as well as the economy of scale in general.

According to Antoninova et al. (2012), the overall outcome of mining is the total disruption of the earth's surface integrity as well as the extinction of biologically active elements such as plant life and animals at all levels of organization. Since the initial state of production to the final state requires the use of water, mining corporations heavily drain fresh water resources, both surface and ground water. Water used in gold production becomes so contaminated that it is no longer useful and cannot support aquatic life. Mining firms' reliance on fresh water assets for gold refining poses a danger to the availability and quality of fresh water in the places where they operate (Agyapong et al., 2012).

The worry is that tainted mining wastewater will seep into the ground water table, poisoning the water to unanticipated levels. The basic risk in underground mining and tunneling, according to another school of thought, originates from significant inflows of ground water when the mine abruptly encounters large water-bearing geology discontinuities (Nevile et al., 1982). The roots of some plants may absorb these heavy metals in polluted water, and some aquatic animals, such as fish, may bioaccumulate them and enter the food chain as a result. Mining appears to have an impact on animals in the air, as massive amounts of particulate matter are emitted into the atmosphere throughout the production process. Birds and other creatures that glide to higher altitudes or leap from the depths are affected by this.

Usage of arsenic

Because arsenic is a metalloid, it has both metallic and non-metallic properties. These characteristics make it a useful doping agent for semiconductor devices like transistors. Other applications include wood preservation and the creation of specialty glass. It's utilized in pyrotechnics and bronzing. During 18th, 19th and 20th centuries, a number of arsenic compounds have been used as medicines, copper acetoarsenite was used as a green pigment (Emsley, 2001).

Research have shown that, arsenic is used in agriculture sector as insecticides to get rid of insects. Arsenic compounds were first utilized as pesticides and wood preservatives in the 1970s. Arsenic was utilized as a cotton desiccant in the 1950s in the United States to boost harvest yield, effectiveness, and affordability (Peryea et al., 2005). Despite its dangers, arsenic is routinely employed in the pharmaceutical sector to make medicines. It's also been utilized in the ceramic and glass industries for special purposes such as resistance to thermal shock, as well as in the food industry as a chicken feed additive (SGS report, 2017).

Chemistry of arsenic in mine wastewater.

Arsenic species in mine wastewater predominates in one form or another under normal oxidation and reduction (Redox) conditions. When conditions favor the medium of reduction, arsenate predominates, while when conditions favor oxidizing conditions, arsenite predominates. Thermodynamic circumstances and experimental studies imply that arsenate predominates at high redox levels and pH more than 10, whereas arsenite predominates at reduced conditions and pH greater than 8 (Swaran et al., 2015).

Their chemical reactivity and destruction is dependent on the redox conditions of the arsenic species, hence, As-bearing sulfide and hydroxide minerals are regulated by redox reactions.

Ecotoxicology of Arsenic

Arsenic is a metalloid, which means it has some of the properties of metals. As a result, when the proper quantity enters the body, it is considered non-toxic and classified as a trace element. Arsenic in its free state is thought to be less or not damaging to the metabolic system. When it is in the speciation form, however, it turns poisonous and releases its harmful effects. When arsenic is in its As^{3+} or As^{5+} speciation and is absorbed into an organism's body, it attaches to the thiol group of enzymes and proteins. This renders the enzymes and proteins inactive and nonspecific, impacting live organisms' metabolic reactions.

According to Jacek et al (2012), high levels of arsenic cause cancer of the respiratory system in those who have been exposed to it for more than 30 years, with of 83.55 percent (Jacek et al., 2012). Eczema, rashes, and tumors leading to skin cancer are among the most common symptoms, according to studies.

A research was carried out in Zloty Stok, a town in Poland which is near to the mine and its immediate surroundings, the concentrations were hundreds of times greater than what is considered usual for the soils found there. A variety of anomalies were discovered, including plant discoloration and partial or complete deformation. A modest number of indigenous plants and trees, as well as a small number of specimens, were also reported (Jacek et al., 2016). Arsenic and arsenic compounds have been recognized as hazardous to living creatures by the International Agency for Research on Cancer (IARC) (Rajakovic et al., 2017).

Arsenic species in water

For environmental protection, it is critical to investigate arsenic species and their behavior in various samples, particularly in natural waters and other environmental spheres. Arsenic is found in a variety of oxidation states, including -3, 0, +3, and +5. Natural arsenic, on the other hand, is divided into inorganic and organic types. Arsenic is a trivalent (III) oxy-anion, whereas arsenate is a pentavalent arsenic (V). When As is in its elemental state, it is non-toxic, but when in its species, it becomes poisonous. Elementary arsenic does not form any reaction with water in the absence of air, however, in natural water, it participates in reduction and oxidation reaction, coagulation and adsorption (Emsley et al., 2003; Mandal et al., 2001).

Arsenic in groundwater

Despite the fact that arsenate is usually assumed to be the most abundant water-soluble species in groundwater, there is growing evidence (Korte and Fernando 1991) that arsenite may be more prevalent than previously thought. Improved sampling, sample preservation, and analytical methods have all contributed to this result. Anderson and Bruland (1991), for example, discovered that it was required to capture AsH_3 produced by As(III) in the field and keep the sample in liquid nitrogen for subsequent laboratory examination.

There were significant discrepancies between those samples and water samples obtained, immediately frozen (-196°C), and then examined in the lab. Andreae (1977) reported that in samples held at -15°C or under dry ice, speciation is unaffected, notwithstanding an early loss of arsenite (about 0.02 ppb). Other sample preservation techniques, according to Korte and Fernando (1991), have been utilized.

Excess Fe(II) and an acidic pH of less than 2 have been suggested as ways to prevent As(III) from oxidizing (Borho and Wilderer 1997). However, because the redox potential of samples from different bodies of water varies, different amounts of Fe (II) are required. As a result, without prior knowledge of the sample, this approach may be difficult to apply to all water samples.

Yalcin and Le (1998) devised a novel method for separating As(III) and As(V) on-site utilizing disposable cartridges. A measured volume of water was pumped through a resin-based strong cation-exchange cartridge followed by a silica-based strong anion-exchange cartridge immediately after collection. DMA was held in the cation-exchange cartridge, but other arsenic species were permitted to flow through. Monomethylarsenoic acid and As^{+5} were retained by the anion-exchange cartridge, while As(III) remained in the solution.

The solution's unretained arsenic was used to calculate the amount of As(III) in the original water sample. DMA was measured in arsenic eluted from the cation-exchange cartridge with 1 M HC1. To determine MMA, the anion-exchange cartridge was first eluted with 0.06 M acetic acid, and subsequently with 1 M HC1 to elute As (V). If the primary arsenic species were merely inorganic As(III) and As(V), the technique may be simplified by employing only the anion-exchange cartridge.

Arsenic in Taiwanese ground waters were speciated via hydride generation (Chen et al. 1994). The oxy species $MexAsO(OH)_3$-x or $As(OH)_3$ are thought to be the arsenic species discovered in groundwater via hydride generation. However, that may not always be the case, particularly in a reducing environment where arsenic and sulfur compounds are predicted to be dominant (Cullen and Reimer 1989). The occurrence of the oxythioarsenate H_3AsO_3S in arsenic-rich terrain has been demonstrated, and capillary electrophoresis revealed that one base extract contained arsenate at 2,616 g/kg of soil and the thio equivalent at 115 g/kg (Schwedt and Reickhoff, 1996).

In three wells in the Blackfoot-disease (BFD) area, the average arsenic content, mostly As(III), was 671 ± 149 µg/L. As(III) to As(V) had a 2.6:1 ratio. The arsenic content reduced to 0.7 g/L outside the BFD area. There were no methyl arsenic species (less than 1 g/L), and concealed arsenic species were not detected. About 3% of the total arsenic in the water from the three wells was insoluble suspended arsenic, and ultrafiltration revealed that about 11% of the soluble arsenic, mostly As(III), was connected with molecules with mass greater than 300,000 daltons. It's possible that the substance was humic (Lu, 1990; Lu and Lee, 1992).

Arsenic in fresh surface water

"Few data exist on the species distribution of arsenic in natural waterways," begins an important research on arsenic species in the Ottawa River, Canada (Sturgeon et al. 1989). At the time of publication, no reports had

suggested the presence of nonhydride-active organic arsenic species (hidden arsenic) in water. The Ottawa River samples were used to create the Standard Laboratory Reference Sample (SLRS-1) for the National Research Council of Canada, which is a river-water reference material for trace metals (NRCC 1986).

The following results (species and concentration in micrograms per liter) were obtained after careful examination of the standard: MMA, less than 0.02; DMA, 0.05; AsC and TMAs, less than 0.01; nonhydride and inactive (hidden) species, 0.12; organically bound, less than 0.01; total arsenic, 0.52 ± 0.03. That reference water had a confirmed value of 0.55 ± 0.08 g/L. The nonhydride and active species accounted for 22% of total arsenic, and the researchers believe the chemical or compounds are similar to AsB. However, the sample's preparation, which included the use of a powerful cation-exchange column, could have altered the species found. For at least 13 months, the arsenic speciation in the sterile water sample (pH 1.6) remained steady.

Anderson and Bruland (1991) employed the Oxidation-Hydride Generation Atomic Absorption Spectrometric (HG-AAS) approach in a study of a number of U.S. lakes and estuaries (primarily in California) (Andreae 1977). Methylarsenicals were found in detectable levels, ranging from 1-59 percent of total arsenic. The methylated forms accounted for 24 percent of total dissolved arsenic in lake surface water, with the exception of two highly alkaline lakes, Mono and Pyramid Lakes. During the late summer and fall, DMA became the major surface arsenic species in the Davis Creek Reservoir, a seasonally anoxic lake. The DMA can be demethylated later in the annual cycle, according to the study. The total-arsenic content varied with the season, and arsenate was the most common inorganic species, albeit arsenite was found in small amounts. For example, the ratio of total arsenic to As(V) to As(III) to DMA in October 1988 was 128:45:12:58. There was no attempt to search those waters for hidden arsenic species.

Studies using a more advanced method of hydride generation on Lake Biwa, Japan (Hasegawa 1997; Sohrin et al. 1997) revealed the presence of methylarsenic(III) species, presumably $MeAs(OH)_2$ and Me2AsOH, in low amounts. The scientists also discovered that arsenic speciation and concentration varied by season, especially in the lake's euphotic southern basin, where DMA can become the dominating species. In coastal waters, seasonal fluctuation in methylarsenic(III) and (V) species was also discovered (Hasegawa 1996). Bright et al. (1994, 1996) found similar compounds in sediment pore water from Yellowknife, Canada, but concealed arsenic species were also detected and were the main species in several samples.

How arsenic spread into environmental spheres.

Arsenic is a naturally occurring element that can be found in rock holding minerals, especially sulfur compounds. Arsenic, on the other hand, can spread into numerous environmental media such as water, soil, and air through volcanism, much of which is caused by human activity. Pesticides, smelter emissions from solid ores such as arsenopyrite in sulfur treatment plants are examples of this (Obiri et al., 2006). Mine tailing is one of the many forms of wastes produced by mining. Tailings, in particular, are a major source of pollution due to unintentional release into the environment (Roussel et al., 2000).

Technologies for arsenic removal

Many academics and scientists have been drawn to arsenic because of its negative effects on the environment. As a result, several technologies for the destruction and removal of arsenic concentrations in soils and wastewater, as well as other environmental sectors, have been developed. Some technologies are included in this category:

- Oxidation
- Coagulation, Precipitation and Filtration
- Ion Exchange
- Sorptive filtration (Adsorption and Activated alumina)

Oxidation

In a redox system, oxidation occurs when a specie gains oxygen or loses hydrogen. Arsenite is converted to arsenate via an oxidation method, which makes it less mobile and allows it to be precipitated and adsorbed onto metal surfaces. This oxidation technology can be carried out in the laboratory using oxidizing agents such as permanganate ($HKMnO_4$), oxygen, and so on. However, research has shown that atmospheric oxygen is the best oxidizing agent for this technology. Th is because, oxidation of arsenite with molecular oxygen is a very slow process. It was also established that the process is exceedingly slow in utilizing ambient oxygen, which causes the entire oxidation process to be prolonged (Pierce and Moore, (1982).

Coagulation, Precipitation and Filtration

The use of coagulation with metal salts, followed by the addition of lime for floc formation, is a more successful means of removing arsenic since 1970s. Three mechanical techniques, namely precipitation, co-precipitation, and adsorption, are used to extract arsenic from the solution (Edward et al., 1994). During the

precipitation process, insoluble chemicals develop. The inclusion of soluble arsenic species into developing metal hydrides phases is then followed by co-precipitation. Co-precipitation with Fe (III) hydrides is a good example. The last phase of coagulation technology is the adsorption process which involves an electrostatic binding of soluble arsenic to external surfaces of the insoluble metal hydrides.

Since 1970s, there has been evidence that coagulation technology is the most successful method for removing arsenic. Coagulation can reduce arsenic concentrations in wastewater from 30ug/L to 5ug/L at a faster pace if mixing and pH are controlled (Sancha et al., 2006). Coagulants such as alum, ferric chloride, ferric sulfate, and aluminum chloride are used to effectively remove arsenic from wastewater. Among the coagulants, ferric sulfate coagulation is one of the best (Johnston et al., 2001).

Ion Exchange

The exchange of ions of the same charge between an insoluble solid and a solution in contact with it is known as ion exchange technology. Water purification, softening, and metal separation are all applications of this technology. Ion exchange uses a synthetic resin with a matrix, which is a cross-sectional connected polymer. Covalent bonding is used to connect functional groups to the matrix. The pH of the water has little or no effect on the procedure (Clifford et al., 1990). Ion exchange technology cannot remove uncharged metal.

Adsorption as sorptive filtration.

Adsorption is a surface phenomenon that is commonly used to remove organic and inorganic contaminants from wastewater. It is a straightforward method in which a solution containing absorbable solutes is drawn to a porous surface structure. As a result of the intermolecular attraction between liquid and solid, some of the solute molecules are concentrated on the solid surface. The outcome is an adsorbate, which is the solute's retention in the adsorption process. There's also adsorbent, which is the solid that it's stuck to. As a result, adsorption is defined as the deposit of adsorbate on the surface of an adsorbent (Nageed et al., 2012).

Activated alumina.

Another application of sorptive filtration for the removal of hazardous elements like arsenic from wastewater. It has a vast surface area that allows most harmful chemicals to be absorbed. Adsorption of contaminants such as arsenic onto the surface of activated alumina happens when water diffuses through the column of activated alumina. The pH of the water and the amount of arsenic in it determine how much arsenic is removed using activated alumina. The grain efficiency of activated alumina, on the other hand, decreases when the point of zero charge is near, as well as at pH 8.2, where the surface is negatively charged. Apyron arsenic treatment unit is a typical activated alumina for arsenic removal (Clifford et al., 1990).

Membrane techniques.

Membrane techniques can easily remove several contaminants from water, including pathogens, salts, and different metal ions. Low-pressure membranes, such as microfiltration and ultrafiltration, and high-pressure membranes, such as Nanofiltration and reverse osmosis, are commonly used in this approach. The removal of arsenic by membrane filtration is unaffected by pH or the presence of other solutes, but it is affected by the presence of colloidal particles. Scaling and membrane fouling can also be caused by iron and manganese. Backwashing a membrane that has been polluted by suspended and dissolved particles in water is not possible. To minimize blockage, water with significant suspended particles must be pre-treated for arsenic removal using membrane techniques (J. Mater., 2012).

Other potential approaches for arsenic removal

Apart from the methods already mentioned, there are other potential approaches for eliminating arsenic contaminants from wastewater and soils and rendering them non-available. Phytoremediation, on the other hand, is the employment of plants to eliminate arsenic contaminants from environmental spheres. Rhizofiltration is another method that involves using plant roots to absorb, adsorb, concentrate, and precipitate metals from the soil. According to research, there is also a biological method that involves the employment of particular types of bacteria that catalyze various biological arsenic elimination processes. Water hyacinth (Eichhornia crassipes), which thrives in streams around the world and has been used as a model system for researching metal ion uptake by aquatic plants, is one of several plant species known to acquire metals from the environment. Biomaterial made from dried water hyacinth roots can be used to remove arsenic from contaminated water in a simple, effective, and low-cost manner. Within 60 minutes of being exposed to a powder made from dried roots, more than 93 percent of arsenite and 95 percent of arsenate were eliminated (Rmalli et al., 2005).

III. Materials And Methods

Introduction

The chapter presents the method used to design this research and the methods for collection and analysis of data. It starts with an overview of the study area, Obuasi Municipality, followed by a brief descriptions and justifications of the parameter to be analyzed in the study followed by data collection procedures as well as activities of Anglo-gold that generate arsenic pollution in wastewater.

Study Area

The Obuasi municipality is one of the forty-three districts in Ashanti Region, Ghana. It was formally part of the then-large Adansi West Municipal District until part of it was taken off in 2003 to form the Obuasi Municipal District. It became operational on February 17th, 2004. Obuasi is the capital of the Municipality, which is located in the southern portion of the Ashanti Region between latitudes 5.35 and 5.65 degrees' north latitude and longitudes 6.35 and 6.90 degrees' north latitude. The eastern section of the municipal, on the other hand, was splintered off to become its own dependent district called Obuasi East District, in 2018.

It has a land area of 1624 square kilometers. In the municipality, there are 53 settlements divided into 19 electoral districts (Ghana Statistical Service, 2012).

Obuasi is known as a major gold producer, with the majority of the people working as miners and only a small percentage of the population working in agriculture.

The research was carried out at Obuasi Township, where the Anglo-Gold Ashanti Obuasi mine's tailing storage facility (T.S.F) and wastewater dams are located. The north dams are located at Kokoteasua and Kwabenafoso, while the south dams are located in the Municipality at Anyinam, Nhyiaeso, and Sanso.

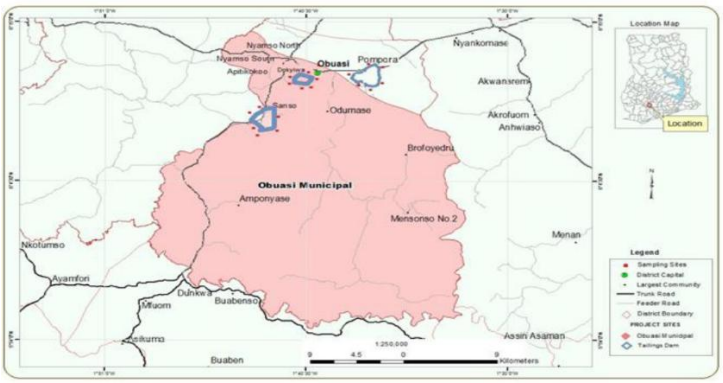

Fig. 3.1 Map of Obuasi Municipality showing the Sanso, Dokyiwa and Pompora tailing dams

Sampling Techniques, Preservation and Storage of samples.

Automatic sampling procedures were used to gather grab wastewater samples from the dams and tailing facilities at regular intervals. The sample was collected using a clean plastic container and a bailer. Refrigeration was used to preserve the samples, and ice was used to preserve them on the field.

5 mL conc. HNO_3 acidification was performed in the laboratory to preserve the samples, which were then held for two months for total arsenic detection.

Sample Preparation

The wastewater samples for the investigation were taken from three different wastewater dams and the Anglo-gold Ashanti Obuasi mine's tailing storage facility (TSF). On a laboratory scale, tests were carried out using the jar test and co-precipitation technology with selective coagulation.

NaOH pellets were used to make a 1M NaOH stock solution for analysis. For laboratory analysis, a 5% stock solution of Ferric Sulphate [$Fe_2(SO_4)_3$] was also prepared. Analytical reagent grade chemicals were employed to make all solutions. 1M NaOH solution was made to alter the pH of the feed water samples.

Coagulation experiment.

Assessment of removal potential with $Fe_2(SO4)_3$

Prior to coagulation, the initial parameters of the raw or the feed wastewater sample was measured and recorded. 1litre of the raw samples were measured and put into five different beaker content labelled **t1, t2, t3, t4 and t5,** respectively. The pH of all the beaker content were adjusted to 11. Equal concentration of the stock solution of ferric salt but different volumes were added to each content of the analytic beakers. An assumed concentration doses 50 ppm for **t1,** 60 ppm for **t2,** 70 ppm for **t3,** 80 ppm for **t4** and 90 ppm for **t5** were tested for detection of arsenic.

Coagulation was performed using jar test method with 3 minutes and 250 rpm rapid mixing with the aid of flocculator. The content of each analytical beaker was then allowed to settle for 30 minutes, decanted and filtered using 0.4 µm pore size membrane filter and are stored for analysis to detect residual arsenic.

All experiments were performed in duplicates to evaluate test reproducibility under identical conditions and all the values represents the average of the duplicate experiments conducted.

Decolourization experiment

The Decolourization of the tailing and wastewater was automatically noticed during the coagulation experiment. However, the experimental protocol for Decolourization experiment was designed as similar as that of coagulation experiment in 3.5.1

Figure 3.2; Picture showing Decolourization of the tailing and wastewater after coagulation experiment.

Analytical methods

Determination of As in the tailing and wastewater

Pallintest Arsenator was used to assess total arsenic in the filtered samples using a colorimetric approach. The procedure measures the color density of the test strip used in the arsenic test in a simple, quick, and accurate manner. In order to determine As using the Pallintest Arsenator, 50ml of filtered water was measured into a conical flask, and two distinct slides (red and black) were put into the cork's designated holes. The test control on the red slide is a lighter arsenic filter, while the arsenic absorber on the black slide is a heavier filter that absorbs the arsenic concentration in the water sample. The black arsenic filter was placed into the arsenator first, then withdrawn after 10 seconds. One pillow of arsenic powder was added to the analyte, followed by one arsenic tablet, which was covered with the cork containing the arsenic filters right away. The exam has a reaction time of 15 minutes. For readings, the black slide was removed from the cork and inserted into the Arsenator.

The arsenator will show readings in a density measurement that are associated to a data table that directly corresponds to the arsenic concentration in the wastewater sample.

Figure 3.3; Picture showing coagulation experiment using flocculator.

IV. Results

Introduction

This chapter outlines the findings of the study. The chapter also presents mean concentrations of both initial and final concentrations of arsenic levels before and after addition of ferric sulphate. It brings to bear the effect of various ferric sulphate concentrations on arsenic and colour. The results have been structured and thematically presented in tables and graphs to give further clarity.

Arsenic concentrations in Tailing Storage Facility (TSF) and Wastewater Dams

Table 4.1 shows the mean concentrations of total arsenic levels in the TSF compared to the wastewater dams given on monthly basis of which samples were taken.

Table 4.1- Shows arsenic levels in Tailings and in Wastewater dams.

Months	As in Tailings (ppm)	As in Dams (ppm)
March	66	18.2
April	74	28.0
May	60	10.6
June	73	9.0
July	93	35.0

Arsenic concentrations in tailing and the wastewater dams were both highest in July followed by that sampled in April. The concentrations were generally higher in the tailings than in the wastewater dams as seen from table 4.1

Arsenic concentrations after addition of Ferric sulphate

Table 4.2 shows the mean concentration of Arsenic in all the 3 different wastewater bodies after addition of Ferric sulphate. In Pond 3, the concentration of Arsenic reduced from 18.15ppm to 0.006 ppm. Wastewater dams A and B reduced to 0.013 ppm and 0.003 ppm respectively after addition of ferric sulphate. The differences between the initial and final concentrations for all three wastewater bodies were significant ($p < 0.05$).

Table 4.2: Arsenic concentrations after addition of ferric sulphate

Wastewater Dams	Mean initial concentration (ppm)	Mean final concentration (ppm)	Percentage removal (%)	p - value
Pond 3	18.15	0.006	99.96	< 0.001
Dam A	31.50	0.013	99.95	< 0.001
Dam B	9.80	0.003	99.96	< 0.001

Effectiveness based on percentage (%) removal

Application of ferric sulphate to all the wastewater dams, the most effective based on percentage removal was confirmed on Pond 3. This was done by;

Effectiveness based on % removal = $\frac{18.15-0.006}{18.15} * 100\% = 99.96\%$

Colour detection after addition of ferric sulphate

Table 4.2 shows the concentration of colour after ferric sulphate was added. In pond 3, the mean final concentration reduced to 2.3 from an initial concentration of 127.0 after the ferric sulphate was added. For tailing dam A and tailing dam B, the initial concentrations reduced to 18.3 and 2.2 respectively. The differences between the concentrations in all the waterbodies was statistically significant ($p < 0.05$).

Table 4.3: Colour concentrations after addition of ferric sulphate

Wastewater dams	Mean initial concentration (pt/co)	Mean final concentration (pt/co)	Percentage removal (%)	p - value
Pond 3	127.0	2.3	98.2	< 0.001
Dam A	399.0	18.3	95.4	< 0.001
Dam B	32.5	2.2	93.2	< 0.001

Effectiveness of decolourization based on percentage (%)

Table 4.3 shows that, there was a significant decolourization of the wastewater after ferric sulphate application. Thus, effectiveness of decolourization based on percentage removal was highest on wastewater Dam A. This is calculated by; Percentage effectiveness (%) = $\frac{399.0-18.3}{399.0} * 100\% = 95.4\%$

Effects of ferric sulphate concentration

Ferric Sulphate Concentration and Arsenic concentration.

Figure 4.1 shows the effects of ferric sulphate on arsenic concentration. It was generally observed that there was a mean reduction of arsenic concentration from 18.15 ppm to 0.06 ppm in Pond-3, 31.5 ppm to 0.013 ppm and 9.8 ppm to 0.03 ppm in Dam-A and Dam-B respectively as the concentration of the ferric sulphate increased. The mean arsenic concentration was least at a ferric sulphate concentration of 70 ppm and the highest was observed in the ferric sulphate concentration of 60 ppm. Concentration of ferric sulphate had an effect on the arsenic concentration in the water bodies with the p-value being 0.0128.

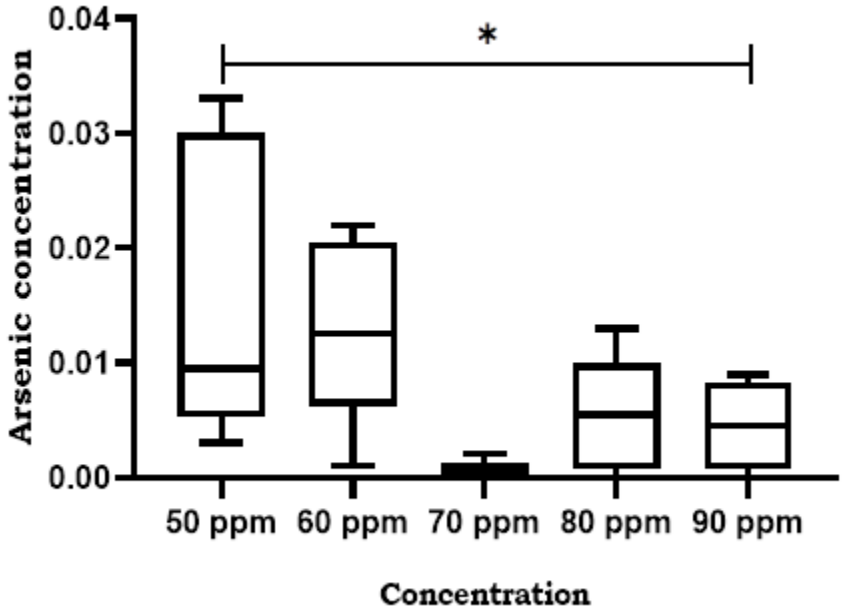

Figure 4.2: Effect of ferric sulphate concentration on Arsenic concentration

Ferric sulphate concentration and colour

Figure 4.2 below shows the effect of varying concentrations of ferric sulphate on colour. It can be seen that ferric sulphate concentrations of 70 ppm and 90 ppm recorded the lowest value for colour (9.0) and the highest value for colour was recorded at a ferric sulphate concentration of 60 ppm (12.5). The varying ferric sulphate concentrations had no significant effect on the value of the colour (p = 0.978)

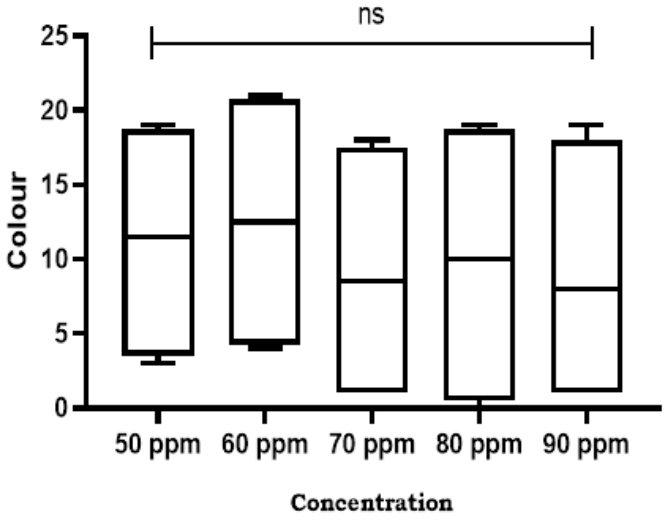

Figure 4.2: Effects of ferric sulphate concentration on Colour

V. Discussion

Activities of Anglo-gold that generate arsenic as heavy metal Pollutant in the wastewater.

Due to its toxicity, persistence, abundance, and potential to bioaccumulate in some aquatic creatures and hence infiltrate the food chain, heavy metal contamination in water bodies has gotten a lot of press around the world.

Heavy metal pollution can come from a variety of sources, including natural processes like volcanism, bedrock weathering, and erosion, as well as manmade activity like industry, agricultural fertilization, mining, metal smelting, and refining.

Despite the huge social and economic benefits of mining, studies have demonstrated that many heavy metal pollutants are released as a result of mining activities. Mineral processing and metallurgical extraction are, however, the primary processes that produce many wastes with high pollutants in mining sectors such as Anglo-gold. The crystallographic bonds of mineral ores are broken during metallurgical extraction in order to retrieve the desired element.

Mineral processing uses physical, chemical, and even biological processes to physically separate and concentrate the mineral ore. Approximately 98 percent of the waste created during mineral processing and metallurgical extraction is in the form of waste.

Gold ores include large levels of sulphide compounds, primarily arsenic-bearing minerals known as arsenopyrite. The waste products containing arsenopyrite are dumped to the mine's tailing storage facility (TSF) after the gold processing. Tailings are the primary waste product of gold extraction and processing, and they are extremely poisonous due to the presence of heavy metals. In a month when gold production is high, the concentration of arsenic in tailings and wastewater dams is higher, as shown in Table 4.1.

Pyrite quickly oxidizes in aerobic conditions in the tailing storage facility, forming iron oxides and residues of arsenic. The oxidation of arsenopyrite is a common route for arsenic distribution into the environment.

Determination of As levels

Heavy metal pollution in water bodies and soils have received great attention Worldwide. This is due to the toxicity of which these heavy metals exert on the environment and the food chain at large. Studies have shown that there has been a reported mass killing of aquatic species upon industrial arsenic discharged (Mirna et al., 2015).

The assessment of arsenic levels of mine wastewater in the tailing dams as well as the effects of coagulant potentials of ferric sulphate for arsenic removal were investigated. The results revealed that, the arsenic levels in the tailings are higher compared to wastewater dams as seen in Table 4.1.

Fresh slurry waste from gold processing after smelting is channeled to the TSF, resulting in a large disparity between the TSF and the wastewater dams. The TSF's opening allows wastewater to passively diffuse from the facility to their respective dams, separating the solid from the water. As a result, a substantial arsenic concentrations are retained in the TSF as compared to the wastewater dams, as seen in Table 4.1.

This supports the theory that toxins in water, particularly heavy metals, diminish with distance traveled. This may be due to the fact that larger creatures, such as plant roots and rock sediments, may provide a trapping effect, resulting in a reduction of arsenic when wastewater flows to the dams (USGS, 1999).

The findings show that arsenic levels in both the tailings and the dams were much higher than the EPA threshold, which is 1 ppm for total arsenic in effluent discharge. According to literature, arsenic pollution causes cancer, nausea, immune system abnormalities, lung cancer, kidney and liver damage, genetic difficulties owing to protein malfunction, and many other health concerns (GSWQ; SDW 2008). When arsenic is exposed to the body, it binds to one of the thiol group of enzymes, thus, inactivating the enzyme's normal action (Hogarh et al., 2016).

Removal potentials of ferric sulphate.

As shown in Table 4.2 and Fig. 4.2, the removal potentials of Ferric Sulphate at various concentrations on total arsenic in all wastewater dams were investigated once more. The elimination potential of ferric sulphate on arsenic increases dramatically as the concentration of ferric sulphate increases. Table 4.2 shows that ferric sulphate has an impact on destruction of higher arsenic levels. As shown in Fig. 4.2, ferric sulphate concentration of 70ppm produced effective results with an estimated mean value of 0.001 ppm. Comparatively, arsenic concentrations of 80 ppm and 90 ppm also gave acceptable results but leaves extra residual parameter of the iron (Fe) which increases cost of removal.

After laboratory analysis, there was an observable drop in colour after addition of the ferric sulphate as reported in Table 4.3. This suggest that, the coagulant does not only affect arsenic but notably, it has a greater effect on other parameters like colour as seen in the projected Fig.4.3.

Ekoloji (2010), found a residual concentration of 8.0 ppm after he investigated in arsenate removal using iron salts of ferric sulfate and ferric chloride as coagulants. Comparing the results recorded from this study to his findings, the same destruction effect was seen after the application of ferric sulfate. However, fig. 4.1 revealed that when a right dosage of $Fe_2(SO_4)_3$ is used, that is at 70 ppm, the residual arsenic was recorded to be 0.00 ppm.

Figure 4.3 shows the effect of varying concentrations of ferric sulphate on colour. It can be seen that ferric sulphate concentrations of 70 ppm and 90 ppm recorded the lowest value for colour 9.0 pt/co. This recorded figure after the experiment tells the effectiveness of ferric sulfate on colour reduction when compared to EPA permissible limit of 150 pt/co for discharge water.

VI. Conclusions And Recommendations

Conclusions

This research discovered that trace elements like arsenic show a pattern of steady decline as they travel from the tailing facility upstream to their respective wastewater dams downstream. According to the study, mining activities result in significant levels of trace element pollution from a variety of sources. As a result, the EPA must check water quality on a regular basis to guarantee that mining businesses' effluent emissions into the environment meet their established requirements. Resource developers and nearby people who uses agro-chemicals for farming, and other life-threatening activities that may introduce arsenic pollution into the environmental media should work together effectively.

Even though such economic activities are operationalized, policymakers must build an integrated water resource management to assure the best strategy to promote the practice in order to have an environment free of pollutants and trace metals.

Recommendations

Literature from this study revealed that, arsenic concentration in waterbodies may come from natural sources. However, higher concentrations along with other trace elements that pollute the environment are from anthropogenic activities such mining. It is therefore recommending that, mining activities should be monitored periodically by appropriate institutions like mineral commission and EPA. Where appropriate, mining companies should be sited from residential places and communities closer to the company should be relocated for which the company must face the full rigor of the cost involved.

I strongly urge the EPA to include in its regulations that any mining activities that contaminate the environment, particularly waterbodies, must be treated even before a permit is obtained for implementation. Prior to the treatment mechanism, I advise all water treatment firms throughout the world to use coagulation with ferric sulphate as the best technique for removing arsenic.

References

[1]. Abraham, M. Y., Wang, Y., Xie, Y., Wei, P., Shaefer III, Henry F., Schleyer, P. Von R., Robinson, Gregory H. (2010). "Carbene Stabilization Of Diarsenic: From Hypervalency To Allotropy". Chemistry: A European Journal. 16 (2): 432–5.
[2]. Actionaid, 2006: The Impact Of Gold Mining On Poor People In Obuasi Ghana.
[3]. Agyapong, E.A., Besseah, M.A., Bernard, Fei-B. (2012), Effects Of Gold Mining On Surface And Groundwater Quality In The Bogoso/Prestea Mining Area.
[4]. Agyemang, P. (1998), Mining And Threats Of The Environment, Chicago Press, USD, Pp. 16-23.
[5]. Ali MA (2006) Arsenic Contamination Of Groundwater In Bangladesh. International Review For Environmental Strategies 6, 329-360.
[6]. Anderson, L.C.D., Bruland, K.W. (1991), Biogeochemistry Of Arsenic In Natural Waters.
[7]. Antwi-Agyei, P., Hogarh, J.N., Foli, G. (2009), Trace Elements Contamination Of Soils Around Gold Mine Tailings Dams At Obuasi, Ghana.
[8]. Andreae, M.O. (1997), Determination Of Arsenic Species In Natural Waters; Analytical Chemistry 49; 820-823.
[9]. Akpalu, W., Normanyo, A.K. (2017), Gold Mining Pollution And The Cost Of Healthcare.
[10]. Bebbington, A., Leonith, H., Luisa, M.B., Warnaars, X. (2008), Mining And The Possibilities Of Development.
[11]. Benjamin, N.A. Aryee., Bernard, K.N., Evans, A. (2012), Trends In Small-Scale Mining Of Precious Minerals In Ghana.
[12]. Bissen, M., Frimmel, F.H. (2003), Arsenic - A Review. Part I: Occurrence, Toxicity, Speciation, Mobility. Acta Hydrochimica Et Hydrobiologica 31, 9-18.
[13]. Blowes D. W, Weisener C. G (2003) Environmental Geochemistry.
[14]. Bruce, A. F, Chem, C. J. (2015), Handbook On Environmental The Toxicology Of Metals (Fourth Edition).
[15]. Borho, M., Wilderer, P. (1997), A Reliable Method For Preservation And Determination Of Arsenic (III) Concentrations In Groundwater And Water Works Samples.
[16]. Chen, Shun-Long., Shiaan, R., Mo-Hsiung., Yang, Kon-Hwa., Chiu, Guan-Ming., Chien, M. Wail. (1994), Arsenic Species In Groundwater Of The Blackfoot Disease Area, Taiwan.
[17]. Clifford, D., Ganesh, G. (1990), Laboratory Study On The Oxidation Of Arsenic 3 To Arsenic 5.
[18]. Cullin, C. R., Reimer, K. J. (1989), Arsenic Speciation In The Environment.
[19]. Davis, A.M., Kaltreider, R.C., Lariviere, J.P. (2001), Arsenic Alters The Function Of The Glucocorticoid Receptor As A Transcription Factor.
[20]. Dondeyne, S., Nduguru, E. (2014), Artisanal Gold Mining And Rural Development Policies In Mozambique.
[21]. Duker AA, Carranza EJM, Hale M (2005) Arsenic Geochemistry And Health. Environmental International 31, 631-641.
[22]. Edwards, M. (1994), Enhanced Coagulation For Arsenic Removal. Journal Of The American Water Works Association 86, 79-89.

[23]. Elangova And Chalakh (2006), Hydrological Process Controlling The Release Of Arsenic In Parts Of 24 Parganas Districts, West Bengal.
[24]. Emsley, J. (2001), Parageneses And Crystal Chemistry Of Arsenic Minerals.
[25]. Foli, G. & Nude, P.M. (2012), Concentration Levels Of Some Inorganic Contaminants In Streams And Sediments In Areas Of Pyro Metallurgical And Hydrometallurgical Activities At The Obuasi Mine, Ghana.
[26]. Gennady, V., Volodymyr. (2017), The Effects Of Arsenic Discrete Distribution On Device Characteristics In Silicon Nanowire Transistors.
[27]. Ghana Statistical Survey Report On Municipal And District Assemblies, (2012).
[28]. Graulau, J. (2008), 'I Mining Good For Development?'; The Intellectual History Of An Unsettled Question.
[29]. Hogarh J.N., Adu-Gyamfi E., Nukpezah D., Osei A., Adu-Kumi S. (2016). Contamination From Mercury And Other Heavy Metals In A Mining District In Ghana.
[30]. Jacek, B., Marta, S., Emelynan, E., Anna, D., Magdalena, B., Paula, V., Anders, O., Fabisiak, J., Galin, G. (2016), Arsenic Concentrations In Baltic Sea Sediments Close To Chemical Munitions Dumpsites.
[31]. Korte, N.E., Fernando, Q. (1991), A Review Of Arsenic (III) In Groundwater.
[32]. Mandal, B.K., Yasumitsu, O., Kazuo, T.S. (2003), Speciation Of Arsenic In Human Nail And Hair From Arsenic-Affected Area By HPLC-Inductively Coupled Argon Plasma Mass Spectrometry.
[33]. Miton, A.H., Hasan, Z., Rahman, A. (2001), Chronic Arsenic Poisoning And Respiratory Effects In Bangladesh.
[34]. Norris, D., Harmens, H. (1990-2005), Spatial And Arsenic Trends In Heavy Metal Accumulation In Mosses In Europe.
[35]. Osae, S., Kase, K., Yamamoto, M. (1995), A Geochemical Study Of The Ashanti Gold Deposit At Obuasi, Ghana. Okayama University, Earth Science Report, 2, 81-90.
[36]. Peryea, F.J. (2005), Sample Washing Procedures Influence Mineral Element Concentrations In Zinc-Sprayed Apple Leaves.
[37]. Pierce, M.L., Moore, C.B. (1982), Adsorption Of Arsenite And Arsenate On Amorphous Iron Hydroxide.
[38]. Rajakovic, L., Vladan, N.R. (2018), Arsenic In Water; Determination And Removal.
[39]. Roussel, C., Catherine, N., Hubert, B. (2000), Mineral Controlling Arsenic And Lead Solubility In An Abandoned Gold Mine Tailings.
[40]. Sancha, M.A. (2006), Review Of Coagulation Technology For Removal Of Arsenic, Chile.
[41]. Schwedt, G., And Rieckhoff, M. (1996), Separation Of Thio- And Oxothioarsenates By Capillary Zone Electrophoresis And Ion Chromatography.
[42]. Smedley, P.L., Kinniburgh, D.G. (2002), A Review Of The Source, Behaviour And Distribution Of Arsenic In Natural Waters.
[43]. Sohrin, Y., Masakazu, M. (1997), Arsenic Biogeochemistry Affected By Eutrophication In Lake Biwa, Japan.
[44]. Spiegel, H., Unger, G., Mifek, M., Lehtinen, T. (2015), Kmno4 Determination Of Active Carbon For Laboratory Routine; Three Long-Term Experiments In Austria.
[45]. Swaran, J.S. (2015), Arsenic Toxicology; 1st Edition.
[46]. Sturgeon, S.N. (1989), An Important Study Of Arsenic Species In The Ottawa River, Canada.
[47]. World Health Organization (WHO). Exposure To Arsenic: A Major Public Health Concern. Available From: Http://Www.Who.Int/Ipcs/Features/Arsenic.Pdf [Accessed May 2011].
[48]. WHO - World Health Organization (1993), Guidelines For Drinking Water Quality, Geneva, Switzerland
[49]. Yalcin, S., And Le, X. C. (1998). Simultaneous Speciation Of Selenium And Arsenic Using Elevated Temperature Liquid Chromatography Separation With Inductively Coupled Plasma Mass Spectrometry Detection.
[50]. Yalcin, S., & Le, X. (2001), Speciation Of Arsenic Using Solid Phase Extraction Cartridges.
[51]. Zhang, X., Cornelis , R., De Kimpe, J. & Mees , L. (1996), Arsenic Speciation In Serum Of Uraemic Patients Based On Liquid Chromatography With Hydride Generation Atomic Absorption Spectrometry And On-Line UV Photo-Oxidation Digestion. Anal. Chim. Acta 319:177-185.
[52]. Zouboulis A, Katsoyiannis I (2002) Removal Of Arsenates From Contaminated Water By Coagulation Direct Filtration. Separation Science And Technology 37, 2859-287