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REVIEW

Acid Mine Drainage: The Footprint of the Nigeria Mining Industry

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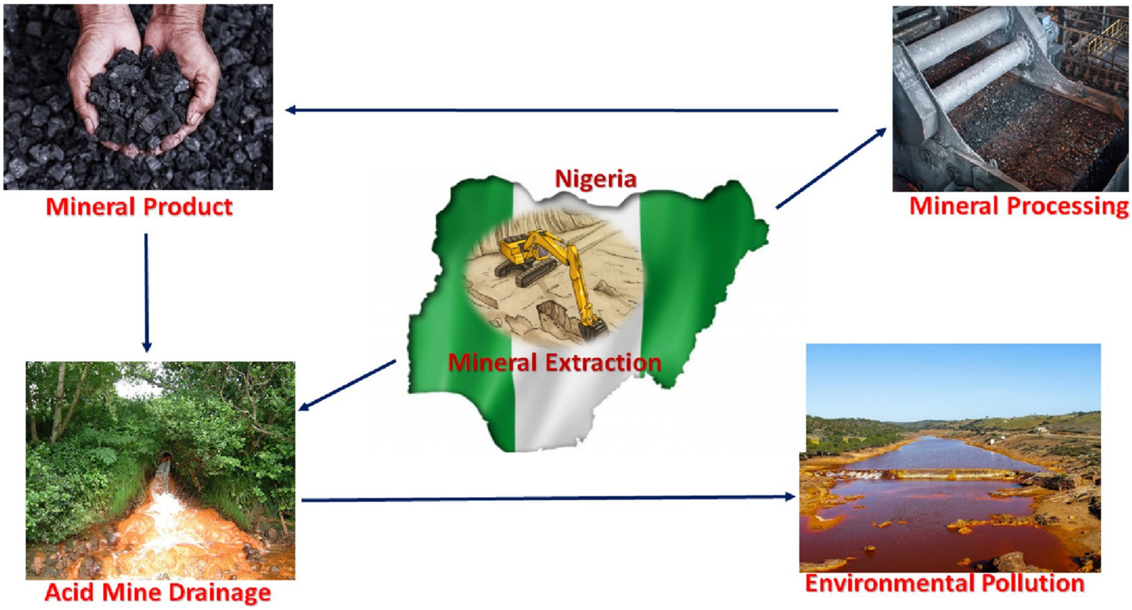
Abstract

Mining of solid minerals in Nigeria has been taking place since the beginning of the last century, and being a developing country with a characteristic lack of proper waste management, this activity has resulted in the production of wastes with serious negative environmental impacts. Acid mine drainage (AMD) has posed a serious challenge to mining host communities globally. However, very little has been documented on its effects and treatment technologies in Nigeria. This paper was aimed at reviewing the effects of effluents from Nigeria's mining industry, with an emphasis on AMD, and the various methods employed in recent times for the treatment of AMD in the country. It was observed that mining wastes and tailings have seriously jeopardized the environment, leading to the ruin of arable lands, pollution of both surface and ground water, and a loss of biodiversity. Adsorption and biological treatment methods are the only methods deployed so far in the treatment of mining effluent pollutants in the country. Both techniques proved to be effective, with a removal efficiency > 80%. Several recommendations were made in this study, including the need for site-by-site assessment of past and active mines so as to identify potential AMD formation and prevent future occurrence. The review also discusses how treatment of AMD can help the country with the actualization of Sustainable Development Goal 6 (SDG 6), which is clean water and sanitation.

Graphical Abstract



Keywords Acid mine drainage · Acid rock drainage · Environment · Mining · Nigeria

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Extended author information available on the last page of the article

1 Introduction

Solid mineral resources are the natural endowment of a nation that includes native metals, industrial minerals, ores, and gemstones on which humans depend for their food, shelter, security, and economic livelihood [1]. Almost no nation can make advances in technology and diversification of its economy with the growth and job security that come with it without being endowed with mineral resources [2]. Nigeria is a country naturally gifted with vast and varied solid mineral resources that are geographically distributed in all the states of the Federation, including the Federal Capital Territory [3]. These minerals are important sources of wealth and have enormously contributed to the country's growth, with associated socio-economic benefits [4]. However, before the minerals are harnessed, they have to pass through stages of exploration, mining, and processing. These processes, especially the mining and processing stages, are often associated with a number of negative environmental impacts.

Environmental pollution is among the biggest problems facing the mining industry globally, and the problem is particularly dismal in developing countries such as Nigeria, where pollution management is very poor. Mining activities threaten the quality and quantity of water resources in many parts of the country due to the various wastes emanating from the process, and most of the time, the mining sites have no appropriate management plans [5]. Mining negatively affects the ecosystem by instigating biodiversity loss, soil erosion, and contamination of both surface and groundwater as well as soil [6, 7]. This degradation in water quality consequently leads to a shortage of water for domestic, industrial, and agricultural purposes [8, 9]. For example, in Enugu, where intensive coal mining occurred, locals who rely on groundwater exploitation through boreholes and shallow (hand-dug) wells, as well as a few surface water bodies (rivers, streams, dams) for all purposes always have these water sources contaminated by mine wastes [10, 11], while over 1000 acres of arable land in Azara, Nasarawa state, have been lost to barite mining-resultant drains, also known as acid mine drainage [12].

Acid mine drainage (AMD), also referred to as Acid rock drainage (ARD) is the flow or seepage of polluted water from old mining areas that may contain heavy metals and radioactive particles depending on the geology [13]. AMD can originate from the mining of sulphide-rich metalliferous ore deposits such as coal. Coal mines are the chief formators of AMD in Nigeria, although occurrences have also been reported in other mining sites such as tin, barite, gold, lead–zinc ore, limestone, among others [5, 12, 14–16]. AMD is a complex pollutant thought to be generated by physical, chemical, and biological factors that include geology, pyrite weathering, and microbial effects [17], and it is the most continuing problem facing the mining industry and affects all environmental flora and fauna, as well as human beings [13]. It is characterized by low pH (as low as pH 2.0), high acidity, and high concentrations of metals and sulphate content. Heavy metals such as lead (Pb), chromium (Cr), silver (Ag), iron (Fe), cadmium (Cd), vanadium (V), molybdenum (Mo), among others, are commonly contained in AMD and their dissolution in water is easily facilitated when the pH is < 4 [18]. These metals can get to people through inhalation, dermal contact, and bioaccumulation, and some of them are extremely toxic even at low concentrations and are potential carcinogens that have been linked to a number of diseases that include cardiovascular and kidney diseases [19–21]. The seepage of untreated AMD into water bodies can cause serious damage to both habitats and water quality, and often leads to an environment devoid of some living creatures and unsuitable for healthy habitation [8, 22]. Aside from AMD, mining activities frequently result in excavations and abandonment of trenches that serve as breading hubs for disease-causing agents and rodents, thus increasing their adverse health effects [23].

The risk associated with AMDs and the release of highly dissolved metal-containing water from mine wastes to nearby water bodies are environmental problems of national interest. As a result, various researchers have studied the level of impact of this problem on various mining sites in various countries. Obreque-Contreras et al. [24] reviewed the characteristics of various AMDs in Chile together with various remediating techniques. Matsumoto et al. [25] employed historical analysis in a bid to find the key factors of AMD using the United States and South Africa as case studies. Ochieng et al. [26] studied the impacts of mining on water resources in South Africa. These reviews are proof of the negative impacts of AMDs on host communities globally and necessitate the need for the environmental parameters of every geographical location suffering from AMDs as well as the remediation efforts to be compiled. Though a large number of studies exist in published literature on AMDs, there is no review to the best of the authors' view that discusses its properties, effects, and the progress made so far in remediating it in Nigeria. On this background, this study was conducted to review the environmental impacts of effluents from the mining industry in Nigeria, with a particular focus on acid mine drainage because of its perpetual consequences on the environment. It also presents the different methods employed so far in the treatment of AMD in the country and, finally, an array of recommendations that should be explored to ensure more sustainable environmental clean-up. It is expected that this study would bridge the knowledge gap in the field to educate the world on the effects of AMDs in Nigeria and what needs to be done to fix this problem to ameliorate the suffering of the host communities.

2 Effects of Mining in Nigeria

Mining is the act of extracting valuable minerals from or beneath the earth's surface. Minerals such as tin, columbite, tantalite, wolframite, lead, zinc, gold, and coal have been mined on a commercial scale since the beginning of the last century and have made huge contributions to the revenue and socio-economic development of the country [4]. The presence of these precious stones in the country has led to an increase in the population, particularly in areas surrounding the ore locations. Figure 1 shows the geographical distribution of solid mineral resources in Nigeria. Although mining has many economic benefits and prospects for the country, including provision of employment, infrastructural development, and serving as raw material to several other industries, it is often associated with various health effects that sometimes outweigh its advantages [27, 28]. Economic and population growth have resulted in an increase in both legal and illegal mineral exploitation, resulting in a wide range of environmental contamination, with water sources bearing the brunt [29]. This puts public health, biodiversity, and aquatic organisms at a major risk.

Figure 1 shows that solid minerals are widely distributed in virtually all parts of the country. Some areas have witnessed more damage than others as a result of the intense mining that took place or is still taking place in those areas. The Abakaliki area is known for hard rock quarrying and mining activities such as limestone (Nkalagu), sandstone (Amaeze), backed shale (Umuoghala), pyroclastic (Ezzagu), and lead–zinc ore (Enyigba), and these activities have led to the generation of AMDs and chemical dissolution of minerals into water bodies [5, 14]. Jos-Plateau is popular for the mining of cassiterite (tin) and columbite. It has been established that the proven tin reserves on the Jos Plateau axis are only about 31,773 tonnes. Other states where tin (cassiterite or tin ore) is mined include Niger, Ondo, FCT Abuja, Kano, Kaduna, Ebonyi, Cross River, Benue, Borno, Bauchi, Adamawa, and Kwara state. This has resulted in extensive anthropogenic environmental degradation, with vast tracks of agricultural land systematically destroyed and increased radioactive waste resulting from mine tailings, dumps, and mine ponds scattered all over the area [31]. Gold is found in Kaduna, Borno, Sokoto, Iperindo in Osun state, Igarain in Edo state, as well as in parts of Niger, Cross River, Kano, Kebbi, Kwara, FCT Abuja, and Zamfara. As at 2016, 181 gold exploration licences were issued by the Nigeria

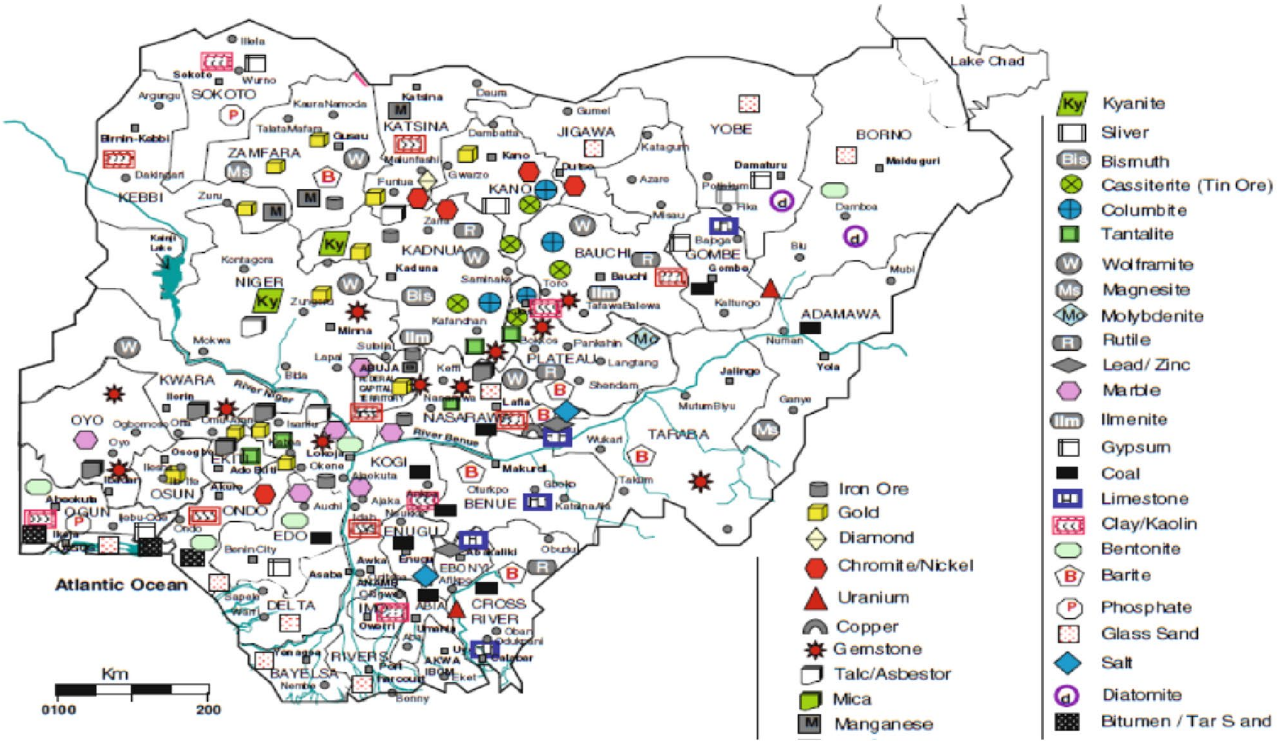

Fig. 1 An overview of the solid mineral resources distribution map of Nigeria [30]

government. Zamfara (especially Sunke and Dareta villages in the state) is renowned for gold ore mining. The high cost of gold has resulted in several illegal mining activities with many consequences for the environment. Lead poisoning attributed to artisanal and incessant gold mining led to widespread infant mortality in Zamfara state in 2010 after lead present in the artisanal mine discharge water drained into the surface and groundwater bodies, which are the water sources of the villagers [32, 33]. This led to the deaths of more than 400 children below the age of five, over 3500 others being impacted, and a number of women experiencing infertility and miscarriages. A similar incident occurred in Niger state, another gold mining hub, in 2015, resulting in the deaths of about 28 children under the age of five, after drinking water poisoned by lead, which was reportedly 17 to 2 times higher than the limits established by the World Health Organization (WHO) [34]. Wastes from mining metals can also result in metals dispersing the mine surroundings with their continuous scattering by wind, erosion, and effluent draining the wastes into agricultural lands, rivers, and ground waters, with climate change leading to seasonal variations in their metallic levels [35].

Table 1 Major minerals associated with coal mines [46]

Mineral	Composition
Pyrite	FeS$_2$
Pyrrhotite	FeI-xS
Marcasite	FeS$_2$
Arsenopyrite	FeS$_2$·FeAs
Bornite	CuFeS$_4$
Chalcopyrite	CuFeS$_2$
Galena	PbS
Sphalerite	ZnS
Millerite	NiS
Covallite	CuS

Coal is regarded as one of Nigeria's most abundant minerals, with an estimated deposit of about 2.8 billion tons [17]. With an estimated reserve of 935 million tons, Nigeria's coal reserves could still be mined for close to 1000 years at a production rate of 400,000 tons per year [28]. Coal is the major cause of AMD and the most researched solid mineral in the country in this regard. The earliest discovery of coal in Nigeria was in Enugu. In fact, the urban status of Enugu state (also known as Coal City State) is due to the presence of very large coal deposits (mainly of sub-bituminous grade) in the state that have been mined since 1916 [36]. Many other coal deposits have been discovered in the country, with occurrences spreading over 13 states of the Federation, but the Enugu coal field remains the most extensive coal deposit [37, 38]. The coal mines in Nigeria created many jobs in the country and served as a source of energy for all and sundry. The industry gave rise to the formation of different sectors in the country, such as the Nigeria railways, Nigeria's electricity corporation, and the Nigeria cement company, and supplied all the energy required by these sectors up to the 1960's [39, 40]. However, the major problem faced by the residents is the constant contamination of water sources by AMD. The acidic nature of the AMDs means the pollutant corrodes mining and plumbing equipment, makes the water moderately hard and also contains high concentrations of total dissolved solids [36]. Coal mining in Enugu produced a large amount of mine waste, which was dumped in landfills and surface dumps and can still be seen in piles and heaps around the mine [41, 42]. The siting of these waste dump sites at the mining peak was chosen for convenience and nearness to waste sources rather than for environmental or geological consideration, leading to environmental deterioration and groundwater contamination [42]. For instance, at its peak, about 18.1 million litres of acid mine waste were released daily from the Enugu coal mine into the Ekulu River [43], and today, almost all pollution reports affecting the chemical qualities of both surface and groundwater in the Enugu metropolitan area are related to coal mining operations [44].

With the discovery of petroleum in the Niger Delta region, the production of coal in the country declined and was almost abandoned. Nevertheless, untreated water from mine ponds and those of underground mines produced during the premier mines and drained into farm lands still pollutes the environment today. The presence of water, alongside oxygen, activates reactions that drain the rocks and produce unwanted environmental pollutants, primarily acid mine drainage [17].

3 AMD in Nigeria

Acid mine drainage can be described as a drainage caused by the natural oxidation of sulphide-containing minerals formed in mined rocks or wastes, or a type of wastewater that emanates from the weathering and leaching of sulphide minerals contained in coal and metalloferrous ores [13]. AMD is primarily formed when sulphur containing rocks are exposed to oxygen and water, which are principal actors in chemical reactions. Upon oxidation, the sulphide decomposes to sulphuric acid, which leaches out soluble metals in concentrations higher than the allowable environmental limits [45]. The process can be chemically or microbially catalysed, but the final chemical composition of the formed AMD will largely depend upon the mineralogy of the host rock [15]. Microbial interactions between members of microbial elements play an important role in AMD formation. Microorganisms such as *Thiobacillus thioxidans* and *Thiobacillus ferrooxidans* serve as biological catalysts and act by utilizing iron sulphide as an energy source to oxidize the sulphide mineral [45]. The overall AMD formation reaction is given in Eq. (1).

$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 8H_2SO_4 \quad (1)$$

Table 1 presents the major sulphur-containing minerals that are responsible for AMD formation, with pyrite being the most common AMD precursor due to its abundance in coal and ores [46].

In some cases, the liquid that is drained from coal stocks, coal handling facilities, coal washeries, and coal waste tips can be highly acidic and, in such cases, can be regarded as acid mine drainage [47]. AMD poses a greater risk in abandoned or artisanal mines than in active mines where drainage can be monitored and treated at the source [48]. The abandoned coal mining sites across the country commonly have coal tailings, which are ore wastes from coal mines with the potential to form AMD once in contact with acidic conditions in effluents [39]. AMD from coal mines is highly acidic and may remain so for three decades after mining [35]. Factors such as hydrology, hydrogeology, mineralogy, geology, climate conditions, and topography influence the level of AMD in both abandoned and active mines [14].

Pollution associated with mining has continued to cause serious environmental concern, especially with regard to water quality issues. Cases of water contamination are rife in Nigeria mines, and this has led to a scarcity of clean water for various activities, consequently hampering the country's economic and social development [29, 44]. Generally, mining activities constitute a major ecological threat because they disturb the soil and lead to soil erosion, pollute water sources, and alter the environment, which may include changes in plant species and loss of biodiversity [3]. The toxicity of water by metals depends on a number of water quality factors that are site-specific, such as pH, hardness, discharge volume, and concentration of dissolved chemical species [16, 49, 50]. AMD can also be toxic to vegetation. Smothering of stream beds by precipitated metal compounds is a common occurrence in AMD-impacted streams [51]. Some studies have shown that contamination from mine waters has significantly contributed to the high volumes of heavy metals in the mining areas and the adjoining communities across the country. Table 2 shows the physicochemical properties of mine waters, ground and surface waters around mines in Nigeria as stated by various authors. To better understand its effect on water resources in the country, drinking water standards as stated by the World Health Organization (WHO) and the Standard Organization of Nigeria (SON) were included for better comparison.

Obasi and Akudinobi [23] studied the occurrence and distribution of heavy metals in the water sources of lead–zinc mining areas of Abakaliki, Southeastern Nigeria. They compared the prevalence of the metals in different communities where active and abandoned mine sites are located. The results showed the occurrence and contamination of several heavy metals, with the concentrations of Mn, Pb, Cr, Ni, Cd, As, Ag, and Se all above the WHO permissible guidelines for drinking water, especially for surface water and areas close to active mines. Water sources within a 7 km radius of active mines were highly polluted and considered unsafe for domestic and agricultural purposes, particularly for drinking and feeding animals. Adigun, Kayode [28] investigated the concentrations of inorganic chemical substances released into surface water bodies from the Okaba coal deposit, Kogi state. Analysis of selected surface water samples revealed that the coal deposit could pose adverse health effects to man through interactions between the surface water and inorganic substances like Fe^{2+}, Mn^{2+}, Pb^{2+}, Cr^{3+}, Zn^{2+}, Cu^{2+}, Cl^- and SO_4^{2-} present in the coal. The average concentrations of Pb^{2+}, Fe^{2+}, Zn^{2+}, Cr^{3+}, and Mn^{2+} in the water samples significantly exceed the limit for drinking water set by the Nigeria Industrial Standard. This contamination is capable of causing AMD. In order to determine the real environmental impact associated with AMD in the Okpara mine and surrounding areas, Sikakwe et al. [44] carried out physical and chemical analysis of water, sediments, and mine dumps from the area. It was found that the pH ranged from acidic (2.84) to moderately acidic (6.05) while the sulphate ion (SO_4^{2-}) which is an indicator of AMD pollution, was in a moderate concentration in all environmental samples. Excessive concentrations of NO_3^- and PO_4^{3-} ions were recorded in the water sample, while concentrations of Al^{3+}, Fe^{2+}, Mn^{2+}, and Ni^{2+}, were much higher than the allowable limits for the relevant chemical species in the Nigeria Standard for Drinking Water Quality. The high concentrations of these metals in the field indicate impending risk as they can easily be washed down into surrounding river banks by various processes of remobilization.

In another study, Nganje et al. [22] investigated the concentrations of major and trace elements in water samples collected in and around Okpara mine to determine the influence of AMD on the quality of water. Results revealed that the water is acidic to moderately acidic with mean pH values of 4.66 and 4.22 in the dry and wet seasons, respectively. Elevated values of Cl, K, Fe, and Mn were observed in areas close to the mine, and this might have impacted the colour of the water. Also, higher values of NO_3 and fluoride were observed in a shallow well downstream from the mine dumps. In general, the chemical quality of the water was found to be above the WHO acceptable level for pH, colour, turbidity, Al, Fe, Mn, and Pb for both seasons. These results indicate that the water quality in the area is significantly influenced by AMD and could have serious implications for human health. Ozoko [54] studied the heavy metal geochemistry of AMD in the Onyeama coal mine and its drainage receiving body, the Ekulu River. The pH values ranged from

Table 2 Water physicochemical properties in and around mining areas in Nigeria

States	Ebonyi[a]	Ebonyi[a]	Enugu[a]	Kogi[a]	Plateau[a]	Ebonyi[b]	Enugu[b]	Plateau[b]	Kogi[c]	Nasarawa[c]	WHO	SON
pH	5.96	5.32	4.22	3.33	7.30	6.34	4.22	6.2	–	–	6.5–8.5	6.5–8.5
Temp. (℃)	–	–	–	–	23.20	–	26.84	25.04	–	–	–	–
E.C. (μS/cm)	–	–	–	–	64.45	–	269.7	67.1	–	–	–	1000
TDS (mg/L)	–	–	–	–	–	–	157.76	–	–	–	600	500
Turbidity (NTU)	–	–	–	–	478.79	–	14.67	20.33	–	–	5	5
TOC	–	–	–	–	–	–	26.84	–	–	–	–	–
Colour (pt/co)	–	–	–	–	–	–	153.11	–	–	–	15 TCU	15 TCU
Total hardness (mg/L)	–	–		–	61.25	–	–	52.83	–	–	–	150
Cu (mg/L)	0.024	0.027	0.00134	0.635	0.05	0.13	0.008	0.05	–	0.09	2.0	1.0
Zn (mg/L)	1.209	1.541	0.25385	4.10	0.053	0.14	0.254	0.025	–	6.60	4.0	3.0
Cd (mg/L)	0.627	1.074	0.00035	–	–	0.24	0.0003	–	0.35	0.68	0.003	0.003
Cr (mg/L)	0.287	0.346	0.00097	0.090	0.0175	0.43	0.001	0.01	1.19	0.26	0.05	0.05
Ni (mg/L)	0.025	0.052	0.0531		0.294	0.09	0.051	0.182	2.01	0.05	0.02	0.02
Pb (mg/L)	1.661	1.802	0.00647	0.05	–	2.18	0.006	–	0.10	21.45	0.01	0.01
Hg (mg/L)	0.496	0.582	–	–	–	0.50	–	–	0.02	0.002	0.001	0.001
As (mg/L)	1.344	0.986	0.00048	–	–	2.10	–	–	0.03	0.001	0.01	0.01
Se (mg/L)	0.474	0.295	–	–	–	0.99	–	–	–	–	0.04	–
Mn (mg/L)	4.709	6.128	3.35	34.49	0.65	1.40	3.35	0.10	–	–	0.10	0.20
Ag (mg/L)	0.388	0.440	–	–	–	0.13	–	–	–	–	0.1	–
Co (mg/L)	0.085	0.738	–	–	–	0.11	0.028	–	0.89	–	–	–
Ca (mg/L)	–	–	–	–	–	–	8.79	–	–	–	–	
Mg (mg/L)	–	–	–	–	–	–	6.77	–	–	–	–	0.20
Na (mg/L)	–	–	–	–	–	–	14	–	–	–	200	200
K (mg/L)			–	–	–	–	12.01	–	–	–	–	–
Al (mg/L)	–	–	–	–	–	–	4.3	–	–	–	0.1	0.2
Mo (mg/L)	–	–	–	–	–	–	0.005	–	–	–	–	–
V (mg/L)	–	–	–	–	–	–	0.0002	–	–	–	–	–
Fe (mg/L)	–	–	5.14	139.97	0.133	–	5.14	0.14	8.01	–	–	0.3
Ba (mg/L)	–	–	0.0694	–	–	–	–	–	–	–	–	0.7
S (mg/L)	–	–	–	–	–	–	33.89	–	–	–	–	–
Cl^- (mg/L)	–	–	–	1096.59	77.623	–	136.67	73.34	–	–	250	250
SO_4^{2-} (mg/L)	–	–	–	19.69	5.063	–	108	3.23	–	–	250	100
NO_3^- (mg/L)	–	–	–	–	1.163	–	567.67	1.7	–	–	–	50
PO_4^{3-} (mg/L)	–	–	–	–	–	–	1.08	–	–	–	–	–
F^- (mg/L)	–	–	–	–	–	–	5.08	–	–	–	–	1.5

Table 2 (continued)

States	Ebonyi[a]	Ebonyi[a]	Enugu[a]	Kogi[a]	Plateau[a]	Ebonyi[b]	Enugu[b]	Plateau[b]	Kogi[c]	Nasarawa[c]	WHO	SON
References	Obasi and Akudinobi [6]	Obasi and Akudinobi [23]	Nganje et al. [41]	Adigun, Kayode [28]	Gyang, Ashano [31]	Obasi and Akudinobi [23]	Sikakwe et al. [44]	Gyang, Ashano [31]	Momoh et al. [8]	Ombugus et al. [11]	WHO [52]	SON [53]

E.C. electrical conductivity, *WHO* World Health Organization, *SON* Standard Organization of Nigeria

[a] Surface water

[b] Ground water

[c] Mine water

2.8 to 4.1, and the major element characteristics of the AMD include high sulphates (> 300 mg/L), dissolved sulphides (1.4 mg/L) and high iron (between 8.4 to 73.11 mg/L). Heavy metal analysis revealed anomalous high concentrations of Pb (278.59 mg/L, 18,570 times greater than the United States Environmental Protection Agency (USEPA) standard), Fe (25.63 mg/L, 86 greater than the USEPA standard), As (21.63 mg/L, 2163 times greater than the USEPA standard) and Cd (34.14 mg/L, 7000 times greater than the USEPA standard). These high concentrations were attributed to the very low pH values of the water. The impact of these results is that the Ekulu River remains highly unsafe for any purpose after four decades of post-mining in the Onyeama coal mine. Water samples from mine ponds, wells and boreholes were collected and analysed to determine the possible pollution arising from leachates in an abandoned mine in Jos, Plateau state [31]. The result showed that the water samples were relatively safe for public use. However, the concentrations of Mn (0.9 mg/L) in the mine pond were found higher than the WHO acceptable limit (0.05 mg/L), while the Cr concentrations of two other samples from mine ponds (0.1 mg/L and 0.12 mg/L, respectively) also exceeded the WHO acceptable level for Cr (0.05 mg/L), thus the need for constant monitoring.

Furthermore, in the areas around lead mining sites in Nasarawa state where the only sources of drinking water available to the residents are shallow groundwater and surface waters, Ombugus et al. [11] assessed the water sources and found that they were contaminated with Cr, Cd and Pb, with concentrations higher than the limits set by WHO and the Nigeria Environmental Standard and Regulatory Enforcement Agency (NESREA), thus putting the locals at risk of diseases as they continue to use the waters for domestic and agricultural purposes. Several other studies have also reported the environmental impact of mining activities in the country [6, 8, 16, 41, 49]. The environmental problems as a result of tin mining also include the destruction of farmlands in search of cassiterite and mine tailings containing radioactive waste that have resulted in several unreported deaths [3]. In addition, artisanal mining has resulted in the pollution of various water sources and several unreported metal poisonings in the country, especially in the rural areas where most of the mines are located [55].

4 Technologies Utilized for the Treatment of AMD in Nigeria

Acid mine drainage from mines can be managed in many ways. It could be recycled into groundwater, disposed of in evaporating ponds, or subjected to treatment for industrial use, agriculture, or portable water supply [8]. The general method of treating AMD is the introduction of an alkaline source to increase the pH above the threshold required by iron-oxidizing bacteria and hence reduce its acidity [56]. It is easier to treat an active mine than an abandoned one because effluents from an active mine can be minimized to its negative effects before being discharged. However, there are no standardized methods for ranking, measuring, and reducing the risk of AMD in an active mine, considering the consequences that follow if any of the variables is miscalculated. Therefore, the particular method employed solely depends on the individual mines [56]. End-of-pipe treatment methods that utilize chemicals were used in the past to treat AMD-contaminated environments. These include lime neutralization, calcium silicate neutralization, ion exchange, and metal precipitation by the addition of sulphides [57]. These passive processes also include the combination of alkaline reagents and the application of neutral biochemical processes in man-made constructed wetlands, ponds, and alkaline-generating drains [51]. Alternatives have been discovered in advanced and cost-effective chemical and biological techniques that are currently in use [57]. These new technologies include adsorption treatment, membrane separation processes, advanced oxidation processes, biological treatment, among others. Ighalo et al. [58] studied these new technologies comprehensively for the treatment of AMDs. However, only a few of these technologies have been employed in the treatment of AMD-contaminated environments in Nigeria. Nonetheless, the methods employed so far in Nigeria and reported in published literature are discussed below.

4.1 Adsorption Treatment

Adsorption is the transfer of solute particles in the aqueous phase to the adsorbent's active sites [59–61]. It is an efficient, convenient, and low-cost wastewater treatment method [62, 63]. Adsorption, which entails the transfer of solute particles from the aqueous phase onto the solid surfaces of adsorbents (active sites), is both a potential and preferable approach for AMD treatment [64, 65]. Its selection is based on environmental, operational, and economical efficiency. Its near-zero-waste drive, achieved through adsorbent reuse, is also noteworthy. Heavy metal pollutants were observed to be the primary target for AMD treatment in Nigeria through the process of adsorption. The summary of the treatment of AMD in Nigeria with the aid of adsorption is presented in Table 3. The performance of an adsorbent can either be determined through its adsorption capacity or through its removal efficiency [66, 67]. Several factors, such as the solution pH, temperature, physical and chemical properties of the adsorbent, reaction or contact time, adsorbent dosage, and adsorbate concentration, are known to affect the performance of the adsorbent [68]. The highest adsorption capacity obtained for the removal of a pollutant present in an AMD in Nigeria is 400 mg/g obtained for the sequestration of Fe^{2+} with the aid of coal ash fly as adsorbent [57].

Olasunkanmi et al. [69] investigated the sorption of Pb^{2+} and Cd^{2+} from AMD using chestnut (*Castanae sativa*) shell as the adsorbent. The removal of Pb^{2+} ion from AMD occurred at the optimum conditions of pH 6 and temperature of 60 °C with a removal efficiency of 97.9%, while the removal efficiency of Cd^{2+} ion was 96.0% at pH 6 and temperature of 50 °C. Orakwue et al. [57] studied the removal of Fe^{3+} from AMD sourced from the abandoned Okpara coal mine in a batch adsorption experiment using three different adsorbents: coal bottom ash, bentonite clay, and coal fly ash. All the adsorbents proved to be effective in the uptake of Fe^{2+} from AMD, with maximum adsorption capacity of 182, 1667, and 400 mg/g for coal bottom ash, bentonite clay, and coal fly ash, respectively. Adetoro, Ojoawo [70] engaged in optimization study using *Azadirachta indica* bark for the adsorption of different heavy metals (Cadmium (II), Copper

Table 3 Summary of adsorptive removal of pollutants from AMD in Nigeria

Adsorbent	Adsorbate	Adsorption capacity (mg/g)	Removal efficiency (%)	Optimum pH	Temp. (°C)	References
Chestnut shell	Pb^{2+}	–	97.9	6.0	60	[69]
	Cd^{2+}		96.0	8.0	50	
Coal bottom ash	Fe^{2+}	182	89.0	2.7	–	[57]
Bentonite clay		1667	84.0		–	
Coal ash fly		400	83.0		–	
Cotton seed hull	Pb^{2+}	27.65	–	–	–	[73]
Azadirachta back activated carbon	Cd^{2+} Cu^{2+} Cr^{3+} Co^{3+} Pb^{2+} Zn^{2+}	–	100	7.0	30	[70]

(II), Chromium (III), Cobalt (III), Zinc (II), and Lead (II)) from wastewater obtained from Morlap marble mining site in Igbeti, Oyo state. For maximum removal efficiencies of the metals (100%), the optimum conditions obtained were pH of 7, temperature of 30 °C, adsorbent size of 2 mm, contact time of 2 h, agitation rate of 150 rpm, and adsorbent dosage of 4 g [70].

Although adsorption is regarded as a critical mechanism in the treatment of AMD, it is not without drawbacks. Because AMD might have a high pollution concentration, it can be difficult to treat large quantities of water before the active sites of the adsorbent are saturated [71, 72]. It was noted that adsorption studies used the elimination of ionic species as their indices, which is quite unsophisticated in and of itself. Total dissolved solids, turbidity, and chemical oxygen demand will provide a more accurate picture of this constraint. As a result, experts do not feel that the advantages of low cost and simplicity of technical application of adsorptive systems can compensate for the disadvantages given by their incapacity to manage water with a high pollution load [58].

4.2 Biological Treatment

Bioremediation is a technique for removing pollutants from the environment that involves the use of plant enzymes, plants, microbial enzymes, or microorganisms [74, 75]. The choice of microorganisms for bioremediation depends on their ability to detoxify, degrade or immobilize pollutants in a particular matrix, while the preferred plant must have a shoot and root system, be fast-growing and be able to resist contamination [76, 77]. In addition, studies are now focusing on the use of organic materials (bio-stimulation) and microorganisms such as sulphate-reducing bacteria, algae (phycoremediation), and fungi (bio-augmentation) for the reduction of heavy metals and sulphate concentrations in AMD. The use of microalgae or macroalgae to treat wastes or wastewater is known as phytoremediation. Bio-stimulation operates by the introduction of nutrients into contaminated soil to improve the growth of indigenous (autochthonous) bacteria, which have higher resistance to pollutants [58]. The bio-stimulation is often accompanied by the introduction of higher laboratory culture bacteria to facilitate the remediation procedure, a process known as bio-augmentation [58].

Oyetibo et al. [55] used a consortium of indigenous bacteria in drains from Onyeama coal mine to successfully bio-remediate the drains. The microbial species present in the AMD were dominated by *Proteobacteria* (50.8%), *Bacteroidetes* (18.9%), *Ascomycota* (60.8%) and *Ciliophora* (12.6%). A consortium of the bacteria effectively removed toxic metals and metalloids (> 70% efficiency) through precipitation, and simultaneously neutralized AMD acidity (pH > 8.2). Abioye et al. [78] designed a phycoremediation method for the removal of heavy metals (As, Cd and Pb) from a heavy metal-rich mining effluents in Minna, Niger state, using two green macroalgae species, *Spirogyra* and *Cladophora*. *Cladophora* absorbed and detoxified more Cd and Pb than As, whereas *Spirogyra* absorbed and detoxified more As than Cd and Pb.. The results showed that phycoremediation using different species of micro and macroalgae can be used to treat water contaminated by metal mining wastes. More comprehensive findings on bioremediation of AMD-contaminated environments in Nigeria are presented in Table 4.

Biological treatment of AMD is often accomplished by biochemically mediated mechanisms that occur inside living organisms. As a result, they are often fairly slow. This type of treatment is the slowest compared to the other major process approaches because longer retention durations are required to achieve acceptable pollutant removal. As a result,

Table 4 Biological methods employed for the treatment of AMD in Nigeria

Biological agent	Contaminated area	Pollutant	Removal efficiency	References
Indigenous bacteria				
Consortium of bacteria	Water	Cd Pb Co Ni As	96.3 94.8 76.9 90.6 88.9	[55]
Pantoea agglomerans	Soil	Cu Pb Fe	60.0 99.6 96.0	[79]
Penibacills sp.	Soil	Ni Pb Hg Cu Zn Cd	97.6 96.8 90.0 86.4 84.9 70.0	[80]
Morganella sp.		Ni Pb Hg Cu Zn Cd	100 98.6 97.5 93.3 80.9 68.4	
Biostimulation				
Pseudomonas aeruginosa	Water	Pb Cr	99.7 95.8	[81]
Micrococcus luteus		Pb Cr	98.2 90.1	
Phycoremediation				
Cladophora	Water	Cd Pb As	88.8 94.9 23.1	[78]
Spirogyra		Cd Pb As	29.0 47.4 82.8	

for such technologies to be used in actual settings involving a huge amount of water, the design is often scaled-up. Larger biological treatment facilities are required to attain the same performance as smaller set-ups for other processes. Furthermore, due to the sensitive nature of biochemically-mediated degradation processes, pH and temperature must be carefully regulated and maintained, or else performance will be reduced or even halted [58].

5 AMD Mitigation and the Sustainable Development Goals

Provision of improved drinking water is paramount for the health and socio-economic development of any nation, especially in a country with a rapidly growing population like Nigeria. In 2015, only 24% of sub-Saharan Africans had access to safe drinking water, defined as water that is readily available when needed and free of contamination [82]. Thus, the aim of the United Nations Sustainable Development Goal 6 (SDG 6), which is clean water and sanitation for all, is to “ensure availability and sustainable management of water and sanitation for all” by 2030 [83]. This target cannot be met in Nigeria without proper management of the daily discharges of wastewater into water bodies across the country by different industries, including the mining industry, since these water bodies serve as the source of water for drinking and other domestic purposes for the majority of the population. The development and use of modern treatment technologies to remediate the impacts of such effluent as AMD and treat contaminated water sources will result in the health and socio-economic development of the citizens, as well as the capacity building of academia as the frontier in research and development. This can be accomplished through the combined efforts of academia, industry, and government. Achievement of SDG 6 will not only provide clean water, but will also create employment for the teeming population. This will, in addition, lead to the accomplishment of other sustainable development goals, such as SDG 3 (good health and well-being), SDG 8 (decent work and economic growth), and SDG 11 (sustainable cities and communities) [84].

6 Research Gaps and Recommendations

During the course of this review, several gaps were discovered. Hence, the following;

1. There are very few studies in Nigeria on the characteristics of AMD and how it affects the environment, even with the large number of both abandoned and active mines in the country. Also, very little has been down to remediate AMD in Nigeria. These studies are very important because it helps in policy making as well as public sensitization. Researchers within the Nigeria clime are enjoined to carry out such studies. Researchers should also endeavour to carry out more research with respect to AMD remediation, including exploring other treatment methods such as the use of different types of adsorbents, membrane separation processes, among others, so as to bridge this gap.
2. Since the formation of AMD is dependent on the mineralogy of the mine, a site-by-site assessment of all past and active mining sites would be required so as to establish the potential and mechanisms of AMD peculiar to each site. Therefore, future studies are encouraged in this regard, even in areas where AMD has not been reported in the past, so as to curb future occurrences of this environmental problem.
3. Most researches done on the characterization of AMD in the country often employ the use of Atomic Absorption Spectrometry (AAS) only. This could be due to the high cost of more complex scientific equipment which has limited the knowledge of AMD composition and mechanism of formation in the country. The government and well-meaning individuals are therefore charged with encouraging and providing the required equipment necessary for research and development in the country.
4. On the technologies utilized for the treatment of AMDs in Nigeria, there is a need for

    i. More research is encouraged on the use of adsorption for the treatment of AMDs in Nigeria. In addition, it was observed that none of the studies analyzed the mechanism of adsorption as well as the regeneration of adsorbents used for the treatment of AMDs. The latter is required in addition to the cost analysis of the process to determine the cost-effectiveness in relation to the efficiency of the adsorbent [85].
    ii. More research is also required on the biological means of treatment in order to avoid leaching or to remediate the environment which has been contaminated by AMD. To do this, the use of bioreactors and other microbes for the reduction of heavy metals and other pollutants such as sulphates and chlorides present in the AMDs is required.
    iii. Other technologies such as membrane technology and advanced oxidation processes (AOPs) for the treatment of AMDs in Nigeria should be encouraged. For membrane technology, the use of membranes such as reverse osmosis, nanofiltration, microfiltration, and hybrids involving the combination of more than one of

these membranes has been shown to be effective in the treatment of AMDs. On the other hand, AOPs processes such as ozonolysis, photolysis, and fenton processes are also encouraged.

5. Environmental policies and regulations on the management of mine wastes and activities, as well as minimum environmental standards, should be implemented to ensure sustainable mining in the country.
6. Public sensitization programs to educate the public on contaminant sources should be put in place by both the government and non-governmental organizations. This will help raise awareness about the harmful effects of mining wastes and tailings, as well as the consequences of artisanal or illegal mining.

7 Conclusion

This paper reviewed the impacts of the Nigeria mining industry on water resources, with an emphasis on acid mine drainage. The environmental degradation and treatment technologies deployed so far in the treatment of AMD in the country were also discussed. It was observed that both abandoned and active mines have seriously affected the environment, especially in the rural areas where most of the mines are located, resulting in biodiversity loss and pollution of common water sources with toxic metals. Adsorption and bioremediation are the two methodologies that have been employed in recent years for the treatment of AMD in the country and have proved to be effective in this regard, with > 80% removal efficiency for most of the metals and metalloid ions. It was also seen that successful remediation of AMD-contaminated water can help the country attain SDG 6, which is clean water and sanitation. Finally, some recommendations were outlined that will help the country achieve more sustainable mining.

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Declarations

Conflict of interest The authors declare that there are no conflicts of interest.

Compliance with ethical standards This article does not contain any studies involving human or animal subjects.

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