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Environmental Health Risks of Coal Mine Leachates in Enugu Metropolis: A Brief Review

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ABSTRACT
This review investigates the environmental and health impacts of coal mine leachates in Enugu Metropolis, Nigeria, which originate from the abandoned Onyeama and Okpara coal mines. These leachates contain high concentrations of toxic heavy metals, including lead, arsenic, cadmium, and mercury, as well as sulphates and acidic compounds. This review examines the chemical composition, toxicity, and pathways of contamination -such as groundwater infiltration, surface water runoff, and soil leaching- associated with these leachates, focusing on their impact on water quality, soil health, and local ecosystems. Local water bodies, particularly the Ekulu and Nyaba Rivers, have been severely affected, with water quality falling far below safety standards, disrupting aquatic life and posing health risks to the local population. The bioaccumulation of toxic metals in crops has further exacerbated these risks, leading to gastrointestinal disorders, neurological damage, reproductive issues, and an increased risk of cancer among residents. Current mitigation efforts, hindered by weak regulatory enforcement and inadequate technological interventions, have been insufficient. The review highlights the urgent need for stringent monitoring, advanced treatment technologies, and enhanced public awareness to address the long-term impacts of coal mine leachates on the environment and public health in Enugu Metropolis.

Keywords: Coal Mine Leachates, Environmental Health Risks, Heavy Metal Contamination, Acid Mine Drainage, Water and Soil Quality, Enugu Metropolis

I. INTRODUCTION

Enugu Metropolis, located in southeastern Nigeria, is a significant urban center known for its rich cultural heritage and historical importance in the country's industrial development. As the capital city of Enugu State, it serves as a hub for political, economic, and social activities in the region. The area is characterized by a tropical climate and hilly terrain underlain by geological formations rich in mineral resources, particularly coal (Figure 1). The metropolis and its surrounding areas are underlain by a series of Cretaceous geologic formations, including the Enugu Shale, Mamu Formation (Figure 2), and Ajali Sandstone, which contain valuable coal deposits [1-4].

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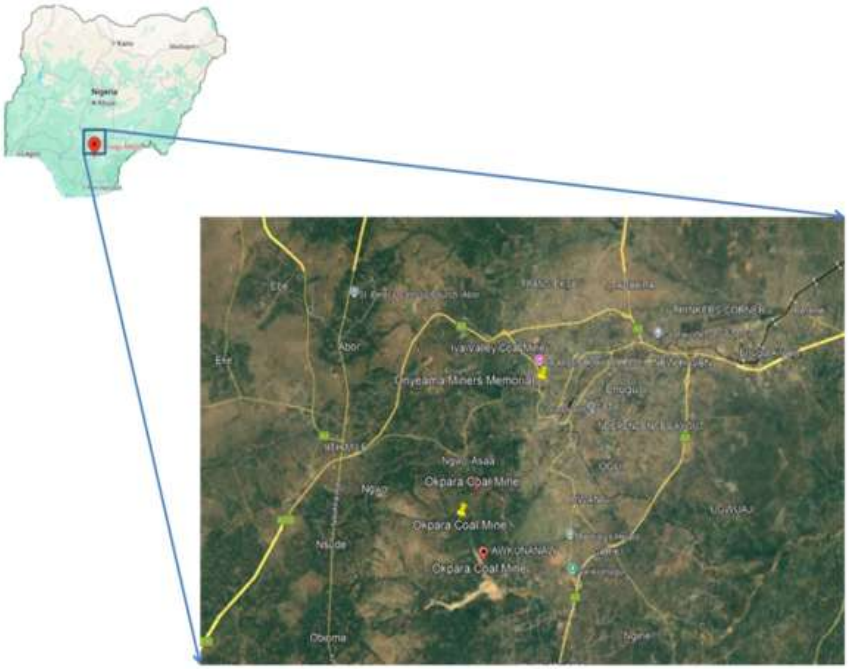

Figure 1: Google Earth Image of Enugu Metropolis showing the locations of Onyeama and Okpara Coal Mines

Historically, Enugu is notable for its coal mining activities, which began in the early 20th century and played a pivotal role in Nigeria's economic development. Coal was first discovered in the Enugu region in 1909, and by 1916, mining operations had commenced [5,6]. The Onyeama and Okpara mines, among others, were central to coal production, managed by the Nigerian Coal Corporation for several decades [7-9]. At its peak, coal mining in Enugu significantly contributed to Nigeria's energy supply and was a major driver of industrialization in the region [5]. However, by the late 20th century, the discovery of oil and the shift towards oil-based energy led to a decline in coal mining activities, culminating in the cessation of operations by 2002[5].

Figure 2: Sections of Mamu Formation showing the Onyeama Coal Deposit

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Since the cessation of coal mining, the once-vibrant mines have been abandoned and left un-reclaimed, leading to significant environmental challenges. The abandoned mines in Enugu Metropolis have become sources of coal mine leachates, which are formed when water interacts with coal deposits and other mining waste materials. These leachates often contain harmful substances, including heavy metals such as arsenic, lead, and mercury, sulphates, and other acidic compounds [10-12]. The interaction of these contaminants with water and the surrounding environment has resulted in severe degradation of water quality, soil health, and ecosystem integrity [13-15].

The environmental impact of coal mine leachates in Enugu is particularly concerning given the region's reliance on groundwater as a primary source of drinking water [14,16-18]. Acid mine drainage (AMD), a common byproduct of abandoned coal mines, poses a severe threat due to its high acidity and elevated concentrations of dissolved metals [19-21]. The process begins with the oxidation of pyrite (FeS_2) in the presence of water and oxygen, producing sulfuric acid and releasing heavy metals from the surrounding rock [7,13]. This phenomenon not only threatens water quality but also has the potential to cause long-term ecological damage and adverse health outcomes for local populations [22,23].The acidification of water sources and the accumulation of heavy metals pose significant risks to public health, potentially leading to gastrointestinal disorders, neurological damage, reproductive health problems, and an increased risk of cancer [24-26]. Mgbeahuruike et al., [27]and Ogbueneet al., [28] confirmed that contaminated water used for agricultural purposes can lead to the bioaccumulation of toxic substances in the food chain, impacting both human and environmental health. The region's climatic conditions, characterized by heavy seasonal rainfall, exacerbate these risks by increasing the dispersion of leachates into surrounding water bodies [7].

The legacy of coal mining in Enugu Metropolis, colloquially known as the "Coal City," stresses the need for a comprehensive understanding of the environmental and health risks associated with coal mine leachates. This review aims to assess these risks and provide a foundation for developing effective mitigation strategies and policy interventions. The objectives of this review are to:

- Assess the environmental health risks posed by coal mine leachates in Enugu Metropolis.
- Examine the pathways through which these leachates impact human health and the ecosystem, including water quality degradation, soil contamination, and bioaccumulation in the food chain.
- Analyze the chemical composition and toxicity of coal mine leachates in the region.
- Evaluate the impact of these leachates on water quality, soil health, and local ecosystems.

II. OVERVIEW OF COAL MINE LEACHATES

Coal mine leachates are liquid effluents generated when water, such as rainwater or groundwater, percolates through coal seams, waste rock piles, and tailings in abandoned or active coal mines [29-31]. As water flows through these materials, it dissolves a variety of substances, creating a complex mixture of contaminants that can pose significant environmental and health risks [29]. In the context of coal mining, leachates are particularly problematic because they often contain harmful substances resulting from chemical reactions between water and the minerals present in coal and associated rocks.

The formation of coal mine leachates is primarily driven by the oxidation of sulfide minerals, such as pyrite (FeS_2), which is abundant in coal seams [32]. When pyrite is exposed to air and water, it undergoes oxidation, producing sulfuric acid and releasing dissolved metals into the leachate [32-34]. This process, known as acid mine drainage, significantly lowers the pH of water, making it acidic and enhancing the solubility of heavy metals(Figure 3). The acidic conditions created by AMD can mobilize metals and other contaminants, increasing their potential to contaminate groundwater and surface water systems [7,30].

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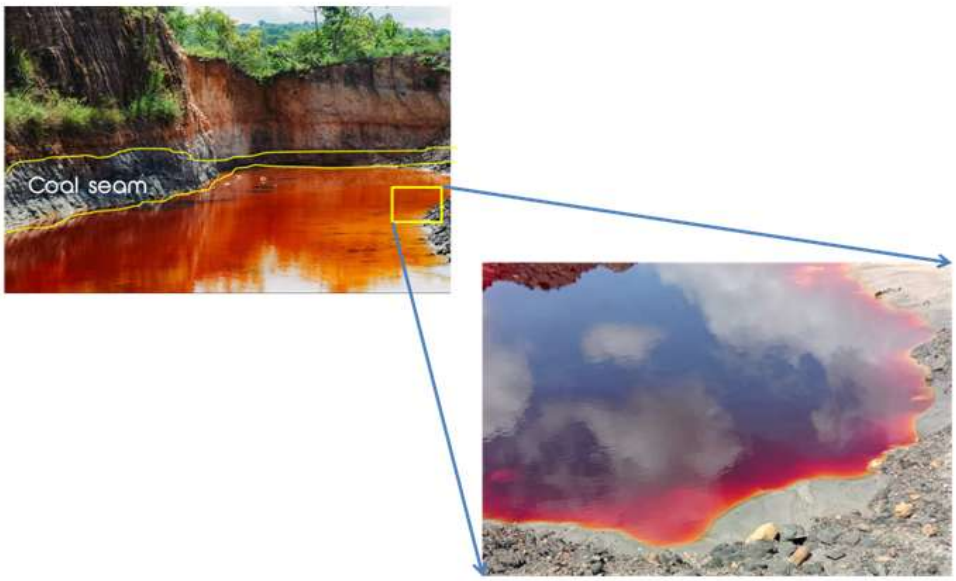

Figure 3: Coal Mine Leachate at the Abandoned Onyeama Coal Mine

Key Contaminants in Coal Mine Leachates

Coal mine leachates typically contain a range of contaminants that can severely degrade water quality and pose risks to both the environment and human health. The primary contaminants found in coal mine leachates include:

- **Heavy Metals**: These include toxic elements such as arsenic, lead, mercury, cadmium, and chromium. Heavy metals are particularly concerning because they can bioaccumulate in aquatic organisms and enter the food chain, leading to serious health problems in humans and animals [7,35,36]. In Enugu Metropolis, studies have found elevated levels of heavy metals in water samples from the Onyeama and Okpara mines, with concentrations that pose potential health risks to local communities [7,37-39].
- **Sulphates and Acids**: The oxidation of pyrite and other sulfide minerals generates sulfuric acid, which significantly lowers the pH of the water. The resulting acidic conditions not only make the water unsuitable for most aquatic organisms but also increase the solubility of heavy metals, further enhancing their mobility and potential to contaminate both surface water and groundwater [32-34]. In Enugu, the pH of water in coal mine areas such as Onyeama and Okpara has been found to range from 3.4 to 6.1, indicating weakly to strongly acidic conditions typical of AMD [7].
- **Other Contaminants**: In addition to heavy metals and acids, coal mine leachates may contain a variety of other contaminants, including nitrates, ammonium, organic pollutants, and particulate matter [40-42]. These substances originate from both mining activities and natural geological processes and contribute to the overall degradation of water quality [7,42]. The presence of organic pollutants, in particular, can add to the toxicity of the leachates [42].

Environmental and Health Impacts of Coal Mine Leachates

The contamination of water bodies by coal mine leachates can have widespread impacts on the environmental. In the Enugu, findings from Ozoko [43] revealed that elevated concentrations of heavy metals and other toxic substances can lead to the accumulation of these contaminants in sediments and bioaccumulation in the food chain. For humans, exposure to contaminated water can result in a range of health issues, from acute gastrointestinal disorders and skin irritations to long-term effects such as neurological damage and cancer [24,25].

The presence of these contaminants also poses significant risks to local ecosystems. Acidic conditions and heavy metal contamination can lead to the loss of biodiversity in aquatic environments, as sensitive species are unable to survive in degraded conditions [43]. In addition, the contamination of soil and water resources can reduce agricultural productivity, impacting food security and livelihoods in Enugu Metropolis [42,43].

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2.2 Sources and Pathways of Leachate Contamination

Leachate contamination in coal mining areas occurs through various processes that transport harmful substances from their sources to the surrounding environment [42]. In Onyeama and Okpara coal mines, leachates are primarily generated when water—whether from rainfall, surface runoff, or groundwater movement—percolates through mine waste, abandoned shafts, or underground coal seams [7,38,42]. This process dissolves and mobilizes contaminants such as heavy metals and acidic components, which subsequently leach into the surrounding soil, groundwater, and surface water bodies [38,42,43].

In Enugu Metropolis, the principal sources of coal mine leachates are the abandoned mines and the extensive network of underground coal seams [7,38]. These sites often remain poorly managed and unmonitored, creating significant points of contamination[7]. The generation of leachates in Enugu is exacerbated by the region's climatic conditions, particularly during the wet season when heavy rainfall increases the rate of water infiltration [42,43]. This leads to accelerated oxidation processes and increased leachate production. Consequently, these leachates can have profound effects on both groundwater and surface water quality in the area [7,38,42,43].

Leachates from coal mining activities can enter the environment through several pathways. Groundwater contamination is a major concern in Enugu, where leachates can infiltrate through soil layers, fractures, and porous rock formations, eventually reaching aquifers [7,44]. Given the shallow water table in the region, there is a high risk of rapid groundwater contamination, which is particularly troubling as many local residents rely on groundwater for drinking and domestic use [45,46]. The acidic nature of the leachates lowers the pH of the groundwater, enhancing the solubility and mobility of toxic metals, which can lead to increased exposure to hazardous substances [7,12,43]. A study by Oyetibo et al., [42] showed that during heavy rainfall, surface runoff can transport leachates from mine sites and waste dumps into nearby rivers, streams, and ponds posing a significant threat. This runoff not only contaminates surface water but also spreads pollutants over a wider geographical area, affecting both urban and rural communities [7,38,42]. In Enugu, mine waters often flow into rivers such as the Ekulu and Nyaba, which are major sources of water for the local population [2,7,47,48]. The contamination of these water bodies has immediate consequences for aquatic life and reduces the suitability of the water for domestic and agricultural use.

Nwachukwu et al., [20] and Ahmad et al., [25] noted that as leachates percolate through the soil, they deposit heavy metals and other contaminants, which can accumulate over time and contaminate the soil. This process degrades soil quality, affecting agricultural productivity and posing additional risks through the bioaccumulation of toxic substances in crops [25]. Acidic leachates can lead to soil acidification, altering the chemical composition of the soil and affecting the availability of essential nutrients [2,7,23,42,43]. This degradation not only impacts crop yields but also poses long-term threats to food safety and public health [23].

III. ENVIRONMENTAL HEALTH RISKS OF COAL MINE LEACHATES

3.1 Chemical Composition and Toxicity

The chemical composition of coal mine leachates in Enugu Metropolis reveals a complex mixture of hazardous substances. These leachates are characterized by exceedingly high concentrations of heavy metals, including lead, iron, arsenic, and cadmium, which are present at levels significantly above safety thresholds for both drinking water and aquatic ecosystems [2,7,42,43].

In samples collected by Ozoko [43] from different points around the Onyeama Coal Mine, lead concentrations ranged from 141.001 mg/L in the Ekulu River at Trans Ekulu to as high as 360.854 mg/L in mine water near Proda. These levels of lead far exceed the U.S. EPA's maximum contaminant level (MCL) of 0.015 mg/L by up to 24,057 times. Similarly, arsenic concentrations were found to vary between 9.892 mg/L (in groundwater before entering the mine adit) and 39.568 mg/L at the mine adit itself, surpassing the MCL of 0.01 mg/L by 989 to 3,957 times [43]. Cadmium levels, another highly toxic metal, were recorded at 11.442 mg/L in groundwater and reached up to 111.000 mg/L at the mine adit, which is 2,288 to 22,200 times higher than the MCL of 0.005 mg/L set by the U.S. EPA. Iron concentrations were also alarmingly high, with values ranging from 3.528 mg/L to 73.113 mg/L, greatly exceeding the safety threshold of 0.3 mg/L by 12 to 244 times [43].

In another study by Akpan et al., [7], the concentration of iron in sediments ranged from 253.4 to 420.1 mg/kg at Okpara mine and from 270.1 to 420.1 mg/kg at Onyeama mine. These

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elevated levels of iron, which are up to 14 times higher than the control site levels of 265.53 mg/kg, are indicative of significant iron contamination, likely due to the oxidation of pyrite (FeS_2) and the associated AMD processes [7]. Zinc concentrations also showed substantial variation, ranging from 15.8 to 21.1 mg/kg at Okpara mine and 14.9 to 25.3 mg/kg at Onyeama mine, which exceeds typical background levels [7].

The presence of these heavy metals in such elevated concentrations poses significant risks due to their ability to bioaccumulate in living organisms [2,7,42,43]. This bioaccumulation is particularly concerning for aquatic life and humans, who are at risk of ingesting these metals through the food chain [7, 24,25]. Prolonged exposure to such high levels of heavy metals can result in severe health issues, including neurological disorders, reproductive toxicity, renal dysfunction, and an increased risk of cancer. Lead and arsenic are particularly troubling because they accumulate in biological tissues over time, leading to long-term health problems such as developmental delays in children and cardiovascular diseases in adults [24,25].

Additionally, the coal mine leachates contain high levels of sulphates and acids, which further exacerbate the toxicological profile of these waters [7,42,43]. The oxidation of sulfide minerals leads to the formation of sulfuric acid, contributing to the low pH values observed in the water samples [7]. The highly acidic nature of these leachates enhances the solubility and mobility of heavy metals in water, increasing their potential to contaminate soil and water bodies [2,25]. Akpan et al., [7] highlighted sulphate concentrations in water samples ranging from 113.9 to 270.2 mg/L, which aligns with the high sulphate levels commonly associated with AMD. The presence of acids and sulphates increases the bioavailability of heavy metals, making them more readily absorbed by living organisms and thus more dangerous [24,25,49,50].

3.2 Impact on Water Quality

Ozoko [43] and Oyetibo et al., [42] observed that coal mine leachates have a substantial impact on the water quality in Enugu Metropolis as pH levels of water bodies affected by these leachates are significantly lower than the acceptable range for potable water (6.5-8.5), indicating highly acidic conditions. The pH of water from the Onyeama Coal Mine ranges from 2.8 to 4.1, reflecting extremely acidic conditions typical of AMD [43].These acidic conditions, coupled with elevated concentrations of heavy metals, lead to significant degradation of water quality, rendering it unsuitable for human consumption and harmful to aquatic life [2,51-53]. The Pollution Load Index (PLI) values for water bodies in proximity to the mines are above one, signifying progressive pollution [43]. Ozoko [43] observed that the concentration of lead in the Ekulu River at New Market Flyover was recorded at 290.140 mg/L, while iron levels reached 18.112 mg/L. These elevated metal concentrations far exceed permissible limits, contributing to the high PLI values and underscoring the urgent need for remediation efforts [43].

A study by Akpan et al., [7] provided further evidence of the impact on water quality, showing that the electrical conductivity (EC) values in the Onyeama mine ranged from 0 to 159.4 µS/cm and from 0 to 349 µS/cm in Okpara mine. The total dissolved solids (TDS) ranged from 0 to 115.5 mg/L at Onyeama and from 0 to 242 mg/L at Okpara. These findings indicate significant variation in water quality, with higher EC and TDS levels suggesting greater contamination in water bodies receiving AMD.The impact on water quality in Enugu is particularly severe, with coal mine leachates increasing both acidity and heavy metal concentrations in groundwater and surface water sources [14, 44]. Groundwater samples from residential areas show poor to very poor quality, with heavy metal levels surpassing the permissible limits established by the World Health Organization (WHO) and Nigerian Standards for Drinking Water Quality [7,14,43]. Surface water bodies are similarly affected, with increased sediment loads and metal concentrations during heavy rainfall events exacerbating water quality degradation and posing risks to aquatic ecosystems [2,7,43,44].

3.3 Soil and Agricultural Impacts

The contamination of soil by coal mine leachates has severe implications for agricultural productivity in Enugu as the presence of heavy metals, like lead and cadmium, in leachates results in their accumulation in soils, animals and crops, posing significant health risks to consumers within and beyond the region [7,43,54]. In agricultural areas near the Onyeama Coal Mine, soil samples have shown lead concentrations as high as 309.636 mg/L and cadmium levels up to 111.000 mg/L[43]. These high levels of heavy metals can impair plant growth, reduce crop yields, and pose health risks to animals and humans consuming contaminated produce [2,7,43,44].

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Sediment samples studied by Akpan et al., [7] from Onyeama and Okpara mines exhibited high levels of manganese (ranging from 15.3 to 150.3 mg/kg) and nickel (10.3 to 50.3 mg/kg). These metals are known to affect soil quality adversely by altering its chemical composition, leading to reduced agricultural productivity and potential bioaccumulation in crops [7,28]. The study also noted that enrichment factor (EF) values for lead and copper in sediments were high, suggesting significant anthropogenic contributions from mining activities [7].

The acidic nature of coal mine leachates also contributes to soil acidification, which negatively affects the availability of essential nutrients like phosphorus, potassium, and magnesium, further degrading soil quality and fertility [2,28,44]. The bioaccumulation of heavy metals in crops grown on contaminated soils poses additional health risks to both humans and animals [28]. In Enugu, where agriculture is a crucial economic activity, this situation is particularly concerning for the local population, many of whom rely on farming for their livelihoods [28,44].

3.4 Human Health Implications

The high concentrations of heavy metals such as lead, arsenic, cadmium, and iron in drinking water sources around the Onyeama and Okpara coal mines present serious health risks to the residents of Enugu Metropolis [7,55,56]. Prolonged exposure to these contaminants, even at low concentrations, can lead to acute and chronic health conditions [24,25]. These include gastrointestinal disorders, neurological damage, reproductive and developmental issues, and a significantly increased risk of cancer [25]. Lead, for instance, is notorious for its ability to accumulate in the body over time, leading to cognitive impairments, particularly in children, and cardiovascular diseases in adults [25,44]. Arsenic exposure is associated with an increased risk of skin, lung, and bladder cancers, as well as cardiovascular diseases. Cadmium and iron, when ingested in significant amounts, can cause renal dysfunction and exacerbate the risk of osteoporosis and other skeletal disorders [2,24,43]. The bioaccumulation of these metals in the food chain further amplifies the health risks, particularly for communities like Ngwo, Uwani, Ugwuaji, and Ogui relying on contaminated groundwater and locally produced crops [7,43,44]. Given the reliance on untreated water sources and the region's socio-economic conditions, the health implications of these leachates are dire, necessitating urgent and comprehensive public health interventions.

Akpan et al., [7], confirmed that continuous exposure to contaminated water from mine sites can lead to chronic health problems due to the ingestion of high levels of metals like lead (16.96 mg/L) and zinc (15.42 mg/L). The potential for bioaccumulation of these toxic elements in humans is compounded by the region's reliance on untreated water sources, which increases the risk of metal poisoning and associated health complications [24,25,44].

Local inhabitants in the Enugu region are exposed to the dangers of coal mine leachates through the consumption of contaminated groundwater, ingestion of crops irrigated with polluted water, and direct contact with contaminated soil [2,7,43]. The concentrations of heavy metals like lead (up to 360.854 mg/L) and arsenic (up to 39.568 mg/L) in water and soil are far above safety limits, leading to health effects such as cognitive impairments, developmental delays, reduced fertility, miscarriages, and birth defects[43,55].

3.5 Ecological and Biodiversity Impact

The introduction of leachates from Onyeama and Okpara coal mines into water bodies causes significant ecological disruption, including a decline in biodiversity [7,42,43]. Elevated levels of metals and acidic conditions in rivers such as the Ekulu and Nyaba have substantially diminished species diversity, affecting ecological balance and ecosystem services [2,7].The Pollution Load Index (PLI) values for sediments in the mining areas are significantly above one, reflecting severe pollution and suggesting that heavy metal contamination from the mines is impacting aquatic life [43]. Also, the high enrichment factors (EF) for lead, zinc, and copper, suggesting ongoing contamination from mining residues [7,43]. This persistent pollution threatens the ecological integrity of aquatic environments by disrupting the habitat and health of fish and other aquatic organisms [7,43].

In aquatic environments, the presence of acidic leachates and high concentrations of heavy metals results in reduced growth, impaired reproduction, and decreased survival rates of aquatic species. Soil contamination from leachates also disrupts terrestrial ecosystems, altering plant community composition and reducing plant biodiversity. These impacts compromise soil fertility and stability, which are vital for maintaining ecological functions and supporting agricultural productivity [2,25,7].

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IV. CURRENT MITIGATION MEASURES AND CHALLENGES

The regulatory framework for managing environmental pollution from mining activities in Nigeria, particularly in Enugu, is notably inadequate, lacking robust enforcement and effective implementation. While environmental laws and regulations exist to mitigate the impacts of mining, they often fall short, leaving significant gaps in addressing the complex challenges posed by coal mine leachate contamination [7,22]. Critical issues include insufficient infrastructure for monitoring, limited financial and technical resources, and the absence of specific guidelines tailored to the unique problems associated with coal mine leachates [43]. The lack of stringent environmental standards, especially for groundwater quality, exacerbates these challenges.Despite some regulatory efforts, such as environmental impact assessments and periodic monitoring, these measures tend to be sporadic and largely ineffective. The insufficient political will to prioritize environmental protection over short-term economic gains further complicates the implementation of necessary mitigation strategies. Effective management of coal mine leachates demands not only the strengthening and updating of existing regulations but also their rigorous enforcement, which requires improved inter-agency coordination, increased funding, and greater public accountability [28].

The challenges are compounded by a general lack of public awareness and political commitment, which hinder efforts to regulate many coal mines. This perpetuates significant environmental and health risks for local populations. Although there have been attempts to introduce water and soil treatment technologies, these efforts are often limited in both scope and effectiveness. Technologies like constructed wetlands and bioremediation offer promising solutions, but their application in Enugu is constrained by financial limitations and technical expertise.Available technological measures for managing leachate contamination include acid neutralization, containment strategies, and advanced treatment systems [28,44]. Water treatment systems, such as lime application and filtration, can neutralize acidic leachates and remove heavy metals. Containment strategies, including physical barriers and liners, aim to prevent water infiltration and leachate generation, though they can be prohibitively expensive. Additionally, revegetation and land rehabilitation efforts are designed to stabilize soil and reduce erosion, but their success depends on appropriate plant selection and ongoing maintenance.

Addressing the health risks associated with coal mine leachates remains particularly challenging due to inadequate monitoring infrastructure, limited funding, and a lack of public awareness. Socio-economic factors, including poverty and political inertia, further exacerbate these issues. Effective management in Enugu requires overcoming obstacles such as limited monitoring capabilities, weak regulatory enforcement, and socio-economic barriers [24,25]. A multi-stakeholder approach involving increased investment in monitoring infrastructure, the strengthening of regulatory frameworks, and enhanced public awareness is crucial for mitigating the adverse effects of leachate contamination and protecting both public health and the environment.

V. FUTURE DIRECTIONS AND RECOMMENDATIONS

This review highlights the urgent need for more comprehensive and targeted research into the long-term environmental and health impacts of coal mine leachates in Enugu Metropolis. Future research should focus on filling existing data gaps, particularly regarding the seasonal variability of leachate contamination, the specific pathways through which contaminants enter the environment, and the direct health effects on local populations. Detailed studies are needed to identify the most hazardous contaminants, their sources, and their bioavailability in different environmental compartments. Furthermore, research should assess the effectiveness of various mitigation strategies, considering the local context and the socio-economic realities of the affected communities [7,28,43].

To address the challenges identified, it is imperative to strengthen the regulatory framework governing coal mine leachates. This involves updating existing environmental laws to set stricter standards for contaminant levels, particularly in groundwater, and ensuring compliance through regular monitoring and the imposition of penalties for non-compliance. Enhancing inter-agency coordination is essential for improved environmental management, alongside developing new policies that account for emerging challenges, such as the impacts of climate change on leachate production and dispersion [28].

Investment in advanced water and soil treatment technologies is critical to effectively manage leachate contamination. Technologies like reverse osmosis and advanced oxidation processes

can significantly improve water quality by removing a wide range of contaminants. Moreover, community engagement should be a cornerstone of mitigation efforts. Involving local communities in monitoring and managing environmental health risks can enhance the effectiveness of these measures and ensure their sustainability. Public awareness campaigns must be intensified, focusing on the dangers of contaminated water, the importance of regular water testing, and safe agricultural practices to prevent the bioaccumulation of toxic substances in the food chain [25,55]. These campaigns should target vulnerable populations and involve multiple stakeholders, including government agencies, non-governmental organizations, and local community leaders.

VI. CONCLUSION

The review highlights the profound environmental and health risks posed by coal mine leachates in Enugu Metropolis. The chemical analysis of these leachates reveals alarmingly high concentrations of heavy metals, acids, and other contaminants, which have led to significant degradation of water and soil quality in the region. The pathways through which these leachates spread—including groundwater infiltration, surface water runoff, and soil contamination—pose severe risks to both human health and the environment, particularly through the bioaccumulation of toxic substances in the food chain. The current mitigation measures and regulatory frameworks are inadequate, lacking the necessary enforcement and technological infrastructure to address the complex nature of leachate contamination. Therefore, there is an urgent need for comprehensive research to close existing data gaps, strengthen regulatory standards, and develop effective treatment and remediation strategies. Community engagement and public awareness are also critical components of a successful mitigation strategy, ensuring that local populations are informed and involved in efforts to protect their health and environment. The legacy of coal mining in Enugu Metropolis serves as a stark reminder of the long-term environmental consequences of industrial activities and the importance of proactive environmental management.

Declaration of competing interest

The authors declare that they have no known competing financial interests.

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