ASSESSMENT OF HEAVY METAL CONCENTRATION IN INDUSTRIAL EFFLUENT FROM A CERAMIC INDUSTRY IN BENIN CITY AND ITS ASSOCIATED HEALTH RISK

BY

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AN UNDERGRADUATE PROJECT SUBMITTED TO THE DEPARTMENT OF ENVIRONMENTAL MANAGEMENT AND TOXICOLOGY, FACULTY OF LIFE SCIENCES, UNIVERSITY OF BENIN, BENIN CITY, EDO STATE, NIGERIA; IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF BACHELOR OF SCIENCE (B.Sc.) DEGREE IN ENVIRONMENTAL MANAGEMENT AND TOXICOLOGY.

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CERTIFICATION

This is to certify that this research titled **"Assessment of Heavy Metal Concentration in Industrial Effluent from a Ceramic Industry in Benin City and Its Associated Health Risk"** was carried out by **Glory Osariemen (Miss)** and presented to the Department of Environmental Management and Toxicology, Faculty of Life Sciences, University of Benin, Benin City, in partial fulfilment of the requirements for the award of the Bachelor of Science (B.Sc.) degree in Environmental Management and Toxicology. It was conducted under suitable conditions, carefully supervised, and approved as having met the requirements for the award of the Bachelor of Science degree in Environmental Management and Toxicology.

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Prof. (Mrs.) E. T. Aisien **Head of Department**	**DATE**

DECLARATION

I, **Glory Osariemen (Miss)**, declare that the project titled **"Assessment of Heavy Metal Concentration in Industrial Effluent from a Ceramic Industry in Benin City and Its Associated Health Risk"** is my original work and that all sources used or quoted have been duly acknowledged through complete referencing. This work has not been submitted previously for any degree at any other university.

______________________________ ______________________

Name of Student **DATE**

DEDICATION

I dedicate this project work to God Almighty for His mercy and faithfulness, and to my family, the Osariemen Family, for their unwavering love, support, and encouragement throughout this journey.

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ABSTRACT

Industrial effluents are significant contributors to environmental pollution, especially in developing countries where waste treatment is inadequate. Ceramic industries generate wastewater that often contains toxic heavy metals capable of accumulating in the environment and posing serious health risks. This study assessed the concentration of heavy metals in effluents discharged from a ceramic industry located in Utesi, Ikpoba-Okha Local Government Area, Edo State, Nigeria, and evaluated the associated potential health risks. Nine effluent samples were collected from three points around the discharge pond over three months. The samples were analyzed for copper (Cu), chromium (Cr), nickel (Ni), lead (Pb), manganese (Mn),and cadmium (Cd) using the Atomic absorption spectrophotometer following standard procedures. Results showed that Mn had the highest concentration (1.07–3.00 mg/L) in July, while chromium was most abundant in June (0.97–1.00 mg/L). Lead and copper ranged between 0.10–0.47 mg/L and 0.10–0.57 mg/L, respectively, while cadmium reached 0.63 mg/L in August. Compared with the WHO and NESREA standards, Cr, Pb, Mn, and Cd exceeded permissible limits. The mean concentration trend was Mn (1.10 mg/L) > Cr (0.58 mg/L) > Pb (0.27 mg/L) > Cu (0.24 mg/L) > Cd (0.22 mg/L) > Ni (0.06 mg/L). Health risk assessment revealed that cadmium posed the highest non-carcinogenic (HQ = 0.43 for children) and carcinogenic risks (CR = 2.62×10^{-4} for children). The total hazard index values were below 1, indicating no immediate threat. The findings show that effluents from the ceramic industry contain heavy metals, especially cadmium and lead, at levels that pose long-term environmental and health risks. Continuous monitoring, effective treatment, and strict compliance with environmental standards are recommended to reduce these risks.

CHAPTER ONE

1.0 INTRODUCTION

Industrialization plays a critical role in national development and economic growth; however, it is also a major source of environmental degradation through the release of hazardous wastes, particularly heavy metals, into surrounding ecosystems. Industries such as ceramics, textiles, tanneries, electroplating, and metallurgy are well-documented contributors to heavy metal pollution due to their use of metallic compounds in various production processes (Nduka and Orisakwe, 2011; Ogundele *et al*., 2019; Khan *et al*., 2025). The ceramic industry, in particular, utilizes a range of metallic oxides and pigments such as lead oxide, cadmium sulfide, chromium oxide, and cobalt oxide to produce glazes and colorants. These substances can become significant sources of heavy metal contamination in effluents discharged into the environment when waste management practices are inadequate (Audu *et al*., 2019; Ezenwajiaku *et al*., 2022; Ogbeide and Henry, 2024)

Heavy metal contamination is a major environmental and public health concern because these elements are not degradable and tend to persist, accumulate, and magnify through trophic levels (Mishra *et al*., 2018). Metals such as lead (Pb) and cadmium (Cd) are particularly toxic even at trace concentrations. Lead exposure has been linked to neurological, hematological, and developmental disorders, particularly in children (WHO, 2017). Cadmium is known for its nephrotoxic and carcinogenic properties, while chromium (especially hexavalent chromium, Cr^{6+}) is associated with skin lesions, liver damage, and respiratory disorders (Adefemi and Awokunmi, 2010; IARC, 2018). Nickel (Ni) and zinc (Zn), though essential in small quantities, can cause gastrointestinal distress, liver, and kidney damage when present in excess (Ogundele *et al*., 2019). Manganese (Mn) has been identified as a systemic toxicant with potential to cause damage to multiple organs (Dey *et al*., 2023).

In Benin City, Edo State, Nigeria, the rapid growth of industrial activities has led to increased generation of industrial effluents, many of which are discharged into open drains, rivers, and nearby lands without proper treatment. The indiscriminate discharge of untreated or partially treated effluents into water bodies and surrounding soil in industrial areas has led to growing concern over the contamination of the environment and its potential health implications (Osaro and Egbe, 2019). Previous studies have reported elevated levels of heavy metals in industrial effluents and adjacent water bodies within the city, indicating poor compliance with environmental regulations and ineffective wastewater management practices (Mokarram *et al*., 2020; Islam *et al*., 2017). The ceramic industry, being one of the emerging industrial sectors in the city, may be contributing significantly to this pollution burden.

Industrial effluents from ceramic industries often contain a mixture of both organic and inorganic pollutants, including toxic metals that persist in the environment due to their non-biodegradable nature (Joseph *et al*. 2019). These heavy metals can bioaccumulate in aquatic organisms, soil, and plants, leading to contamination of the food chain and posing severe health risks to humans and animals alike (Nkwunonwo *et al*., 2020; Okereafor *et al*., 2020; Sardar *et al*., 2013; Sonone *et al*., 2020). Due to their non-biodegradable nature, these metals accumulate in soil and water, posing serious ecological and health risks (Jadaa and Mohammed, 2023; Akharame *et al*., 2017). The health risks associated with exposure to heavy metal-contaminated effluents can occur through multiple pathways, including direct contact with contaminated water, ingestion of contaminated crops or fish, and inhalation of metal-laden dust particles (Gouda *et al*., 2025). Chronic exposure to such metals can lead to bioaccumulation in human tissues, causing adverse health effects such as cancers, organ failure, reproductive disorders, and impaired cognitive function (WHO, 2017; Nduka and Orisakwe, 2011). Therefore, assessing the concentration of heavy metals in industrial effluents from ceramic industries is essential for understanding the extent of contamination, identifying potential sources, and estimating the associated ecological and human health risks.

1.1. Aim of the Study

The aim of this study is to assess the concentration of heavy metals in industrial effluents discharged from a ceramic industry in Benin City, Edo State, Nigeria, and to evaluate the associated potential health risks.

The specific objectives of this study are to:

1. Quantify the concentrations of selected heavy metals in the effluent samples using appropriate analytical techniques.
2. Compare the obtained heavy metal concentrations with the permissible limits set by the World Health Organization (WHO) and National Environmental Standards and Enforcement Agency (NESREA)
3. Assess the non-carcinogenic and carcinogenic health risk indices for the heavy metals.
4. Provide recommendations on measures to minimize heavy metal discharge and improve industrial effluent management in the ceramic industries within Benin City.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Industrial Effluents and Environmental Pollution

Industrial effluents refer to the liquid waste streams generated from diverse industrial processes such as manufacturing, chemical production, mining, and agro-processing (Okereke *et al.,* 2016). These effluents are complex mixtures that typically contain water, organic and inorganic compounds, suspended solids, heavy metals, and sometimes toxic or hazardous substances. The characteristics of industrial effluents vary greatly depending on the type of industrial activity, the nature of raw materials used, production techniques, and the level of treatment carried out before discharge into the environment (Sathya *et al.,* 2022).

Physically, industrial effluents are often identified by high turbidity, coloration, offensive odors, and elevated temperatures, which can significantly modify the quality of receiving ecosystems. For instance, effluents from textile industries frequently contain dyes that impart coloration to water bodies, while those from food processing industries are usually rich in organic matter, leading to high biochemical oxygen demand (BOD) (Khandare and Govindwar, 2015).Chemically, industrial effluents often contain toxic heavy metals such as lead, cadmium, and mercury, as well as organic pollutants including phenols, pesticides, and solvents. They may also contain acids, alkalis, and salts that can drastically alter effluent pH, making it either highly acidic or alkaline (Gupta *et al*., 2012). Biologically, some effluents harbor pathogenic microorganisms or contribute to nutrient enrichment, particularly with nitrogen and phosphorus, which may lead to eutrophication in aquatic systems (Carpenter *et al*., 1998).

The volume and flow rate of industrial effluents differ widely, ranging from small-scale discharges from artisanal industries to millions of liters per day from large industrial complexes (UNEP, 2016). When discharged without proper treatment, industrial effluents pose severe risks to ecosystems and human health, contaminating water bodies, degrading soil quality, and threatening biodiversity. The complex and hazardous nature of industrial effluents underscores the importance of efficient management and effective treatment systems to minimize their environmental impact.

2.2 Major Sources of Industrial Wastewater in Developing Countries

In developing nations, industrial wastewater arises from a wide range of sectors, driven by rapid industrialization, economic expansion, and weak enforcement of environmental regulations. Major contributors to industrial effluents include textile and dyeing industries, food and beverage processing plants, chemical and pharmaceutical industries, mining and metallurgical operations, petroleum and petrochemical industries, and small-scale or informal production activities (Ogbeide and Henry, 2024).

Textile and dyeing industries, particularly common in countries such as India, Bangladesh, and Nigeria, generate substantial wastewater containing dyes, salts, and various finishing chemicals. Azo dyes, which make up about 70% of textile dyes, are notably persistent and carcinogenic, posing significant risks to both ecological and human health (Berradi *et al*., 2019). Food and beverage processing industries such as breweries, sugar refineries, and palm oil mills produce effluents rich in organic matter, with very high BOD and chemical oxygen demand (COD). In Nigeria, for instance, palm oil processing effluents have been reported to possess BOD values exceeding 20,000 mg/L, thereby severely polluting nearby water bodies (Ohimain *et al*., 2013).

Chemical and pharmaceutical industries discharge effluents that contain solvents, active pharmaceutical ingredients, and heavy metals, many of which are toxic and resistant to biodegradation. Mining and metallurgical industries, especially artisanal mining prevalent in Africa, release effluents laden with suspended solids and heavy metals, further compounding water pollution problems (Ogbeide and Henry, 2024). The petroleum and petrochemical sectors, which dominate the Nigerian economy, tend to discharge hydrocarbons, phenols, and sulfides into the environment, with devastating effects on aquatic life.

Additionally, informal industries such as leather tanning, battery recycling, and soap production also contribute to pollution due to their rudimentary technologies and lack of effluent treatment systems. The pace of industrial expansion in developing regions often surpasses the growth of environmental infrastructure, leading to the uncontrolled release of untreated effluents into rivers, streams, and coastal waters. This widespread pollution not only degrades ecosystems but also poses serious public health challenges (Grema *et al.* 2022; Hamidu *et al.,* 2021).

2.3 Composition and Environmental Impact of Untreated Effluents

The composition of industrial effluents varies considerably depending on the nature of industrial processes involved. Typical constituents include organic pollutants such as hydrocarbons, phenols, and organic acids, which elevate BOD and COD levels, depleting dissolved oxygen in water and causing mass mortality of aquatic organisms (Ogbeide and Henry, 2024). Inorganic pollutants, including heavy metals like chromium, lead, and cadmium, as well as various salts, accumulate in soil and aquatic systems, leading to long-term toxicity. Chromium, a common pollutant from tannery industries, is recognized as a potent carcinogen with serious environmental and health effects (Sawalha *et al*., 2020).

Nutrient-enriched effluents, particularly those containing nitrogen and phosphorus, promote eutrophication, which triggers algal blooms and hypoxia, thereby disturbing aquatic ecosystems. Effluents from abattoirs and food processing industries may also carry pathogenic microorganisms such as *Escherichia coli*, directly threatening human health. Furthermore, the discharge of hot effluents from power plants and refineries contributes to thermal pollution, which alters aquatic habitats and stresses aquatic species.

The environmental effects of untreated effluents are multifaceted. Water pollution remains the most critical issue, as contaminated surface and groundwater become unsuitable for drinking, irrigation, or domestic use (Oyeku and Eludoyin, 2010). Heavy metals bioaccumulate in aquatic organisms, entering the food chain and causing toxic effects in humans (Ali *et al*., 2019). Soil contamination from effluent disposal reduces soil fertility, alters pH, and introduces toxic elements that hinder agricultural productivity. Air quality may also deteriorate due to volatilization of organic compounds (VOCs) from effluents, causing respiratory issues in nearby communities.

Biodiversity loss is another serious consequence, as pollutants destabilize both aquatic and terrestrial ecosystems. In Nigeria's Niger Delta, oil effluents have destroyed mangrove ecosystems and severely disrupted biodiversity (UNEP, 2011). Health impacts are equally alarming, with effluent-polluted water linked to outbreaks of waterborne diseases such as cholera and dysentery, as well as chronic ailments including cancer and neurological disorders associated with heavy metal exposure (WHO, 2017). These far-reaching impacts highlight the urgent necessity for sustainable wastewater management and strict enforcement of environmental protection policies.

2.4 Overview of Nigeria’s Industrial Pollution Scenario with Focus on Benin City

Nigeria, as the largest economy in Africa, faces acute environmental challenges arising from its industrial sectors, particularly in metropolitan centers such as Lagos, Port Harcourt, and Benin City. The country’s industrial pollution is driven by its oil and gas sector, burgeoning manufacturing industries, and agro-processing enterprises, compounded by weak regulatory enforcement and inadequate waste treatment facilities.

The oil and gas industry, concentrated in the Niger Delta, has been identified as a major contributor to environmental degradation. According to a United Nations Environment Programme (UNEP) report, oil pollution in Ogoniland resulted in benzene concentrations in groundwater up to 900 times above the World Health Organization’s permissible limits (UNEP, 2011). Other industries, including textile manufacturing, breweries, and palm oil processing, further deteriorate water quality through the discharge of untreated effluents into major rivers such as the Ogun, Osun, and Ikpoba.

Despite the existence of regulatory frameworks such as the Environmental Impact Assessment Act of 1992 and the establishment of the National Environmental Standards and Regulations Enforcement Agency (NESREA), enforcement has been hampered by limited funding, corruption, and poor technical capacity (Eze, 2018). The World Bank (2020) estimated that pollution-related illnesses cost Nigeria between 1–2% of its GDP annually, reflecting both economic and social burdens.

In Benin City, Edo State, industrial pollution presents a growing environmental threat due to the city’s concentration of rubber processing, palm oil production, breweries, and metal fabrication industries. Effluents from these activities, particularly those discharged into the Ikpoba River, have been reported to contain elevated levels of BOD, COD, and heavy metals such as lead and Cadium (Ekhaise and Anyasi, 2011). These pollutants have rendered the river unsuitable for domestic use and have contributed to the decline in fish populations. In Benin City, Akharame *et al*. (2017) assessed the concentrations of heavy metals in effluents from four major processing industries—namely a carbonated soft drink factory, a brewery, a glass manufacturing company, and a meat-processing plant. Their results revealed that the concentrations of Zn ranged between 1.90 and 2.11 mg/L, while lead levels were about 0.03 mg/L in some effluents. These values were found to exceed the permissible limits set by the Federal Ministry of Environment (FMEnv) and the World Health Organization (WHO), particularly for Zn and Pb. The study concluded that most industries in Benin City were not compliant with environmental standards, thereby contributing significantly to the degradation of nearby water bodies and soils.

Similarly, Ochu *et al*. (2025) carried out a detailed investigation of heavy metal concentrations in manufacturing and beverage industry effluents, including those from the Seven-Up bottling plant in Edo State. Their findings showed alarmingly high levels of metals such as iron (6.68 mg/L), Ni (6.65 mg/L), Zn (5.65 mg/L), and crnium (4.53 mg/L), all of which exceeded the WHO and national regulatory limits. This study provided strong evidence that industrial activities within Benin City and its environs release significant amounts of toxic metals into the environment, posing ecological and health risks to communities relying on surface and groundwater sources for domestic use. The study therefore emphasized the urgent need for stricter monitoring, periodic environmental audits, and the enforcement of effluent treatment policies in industrial zones across Edo State.

Small-scale industries, including soap and detergent manufacturing, metal works, and local tanneries, contribute additional loads of untreated wastewater into drainage systems and surrounding lands. Groundwater contamination from effluent seepage has been reported, leading to increased nitrate and metal concentrations in borehole water supplies. Communities located near polluted rivers have reported health issues such as gastrointestinal disorders, skin infections, and respiratory diseases associated with exposure to polluted water and air (Omofonmwan and Eseigbe, 2009).

While the Edo State Environmental Protection Agency (ESEPA) and other relevant bodies are responsible for monitoring industrial discharges, their operations are constrained by inadequate resources. Although some industries have adopted primary treatment systems, advanced technologies like bioremediation and reverse osmosis are largely unaffordable. Strengthening local environmental governance, fostering public-private partnerships for wastewater treatment, and encouraging cleaner production technologies are essential for addressing industrial pollution in Benin City.

2.5 The Ceramic Industry and Effluent Generation

The ceramic industry plays a significant role in global manufacturing, producing a wide range of products, including tiles, sanitaryware, tableware, and technical ceramics. The production process, raw materials, and associated effluent generation contribute to environmental challenges that require careful management.

2.5.1. Ceramic Manufacturing Process

The ceramic manufacturing process involves several stages to transform raw materials into finished products. The process begins with raw material preparation, where natural materials are crushed, ground, and mixed with water to form a homogeneous slurry or slip (Barbosa *et al.*, 2018). This mixture is then shaped using techniques such as pressing, extrusion, or slip casting, depending on the desired product. The shaped products undergo drying to remove excess moisture, ensuring structural integrity before further processing. Glazing follows, where a vitreous coating is applied to enhance aesthetic appeal and durability. The final stage, firing, occurs in kilns at high temperatures (800–1400 °C), which solidifies the ceramic structure and fuses the glaze to the surface (Martins and Costa, 2020). Additional post-firing processes, such as polishing or cutting, may be applied for specific products like tiles.

2.5.2. Raw Materials Used

The primary raw materials in ceramic production include clays and non-plastic materials. Clays, such as kaolinite, illite, or montmorillonite, provide plasticity, enabling the material to be molded (Silva *et al.*, 2019). Non-plastic materials, including quartz and feldspar, contribute to the structural stability of the final product. Glazes are formulated from silica, fluxes (e.g., sodium or potassium compounds), and stabilizers (e.g., alumina) to achieve desired surface properties, such as gloss or water resistance (Ribeiro *et al.*, 2021). Colorants, typically metal oxides like Fe, Co, or Cr, are added to impart specific colors. Additionally, processing additives, such as deflocculants (e.g., sodium silicate) and organic binders, are used to improve workability and consistency during production.

2.5.3. Stages of Effluent Generation

Effluent generation is a significant environmental concern in ceramic manufacturing, occurring at multiple stages of the process. During raw material preparation, washing and grinding operations produce wastewater containing suspended clay particles, fine solids, and dissolved minerals. Slip casting and glazing generate effluents with high concentrations of particulate matter, heavy metals from glazes and colorants, and organic additives (Chong *et al*., 2015). The firing stage may produce scrubber water from gas cleaning systems, which contains particulate matter and chemical residues from kiln emissions. Polishing and cutting processes generate sludge with high solid content, often mixed with cooling water. Studies estimate that ceramic production generates approximately 0.5–1.5 liters of wastewater per kilogram of product, depending on the process and product type (Gomes *et al*., 2022).

2.5.4. Common Pollutants in Ceramic Effluents

Ceramic effluents are characterized by a range of pollutants that pose environmental risks if not properly managed. Suspended solids, primarily clay particles and silica, contribute to high turbidity and sedimentation in water bodies. Heavy metals, such as Pb, Cd, Zn, and Cr, originate from glazes and colorants and are particularly concerning due to their toxicity and persistence (Fernandes *et al*., 2017). Inorganic salts, including sulfates and chlorides, are introduced through raw materials and additives, increasing the salinity of effluents. Organic compounds, such as binders and deflocculants, may also be present. The pH of ceramic effluents can vary widely, often being alkaline due to the presence of fluxes and alkaline additives.

2.5.6. Previous Studies on Ceramic Industrial Wastewater Contamination

Several studies have investigated the environmental impact of ceramic industrial wastewater. Chong *et al*. (2015) analyzed effluents from tile manufacturing and found high concentrations of suspended solids (up to 10,000 mg/L) and heavy metals, particularly Zn and Pb, exceeding regulatory limits in untreated discharges. Fernandes *et al*. (2017) reported that heavy metal contamination in ceramic effluents can bioaccumulate in aquatic ecosystems, posing risks to both environmental and human health. Research by Almeida and Silva (2020) highlighted the challenges of treating ceramic wastewater due to its complex composition, recommending advanced treatment methods like coagulation-flocculation and membrane filtration to remove solids and metals effectively. Gomes *et al*. (2022) emphasized the potential for wastewater recycling in ceramic production, noting that up to 70% of water could be reused with appropriate treatment, reducing environmental impacts and operational costs. These studies underscore the need for improved wastewater management practices in the ceramic industry to mitigate pollution and comply with environmental regulations.

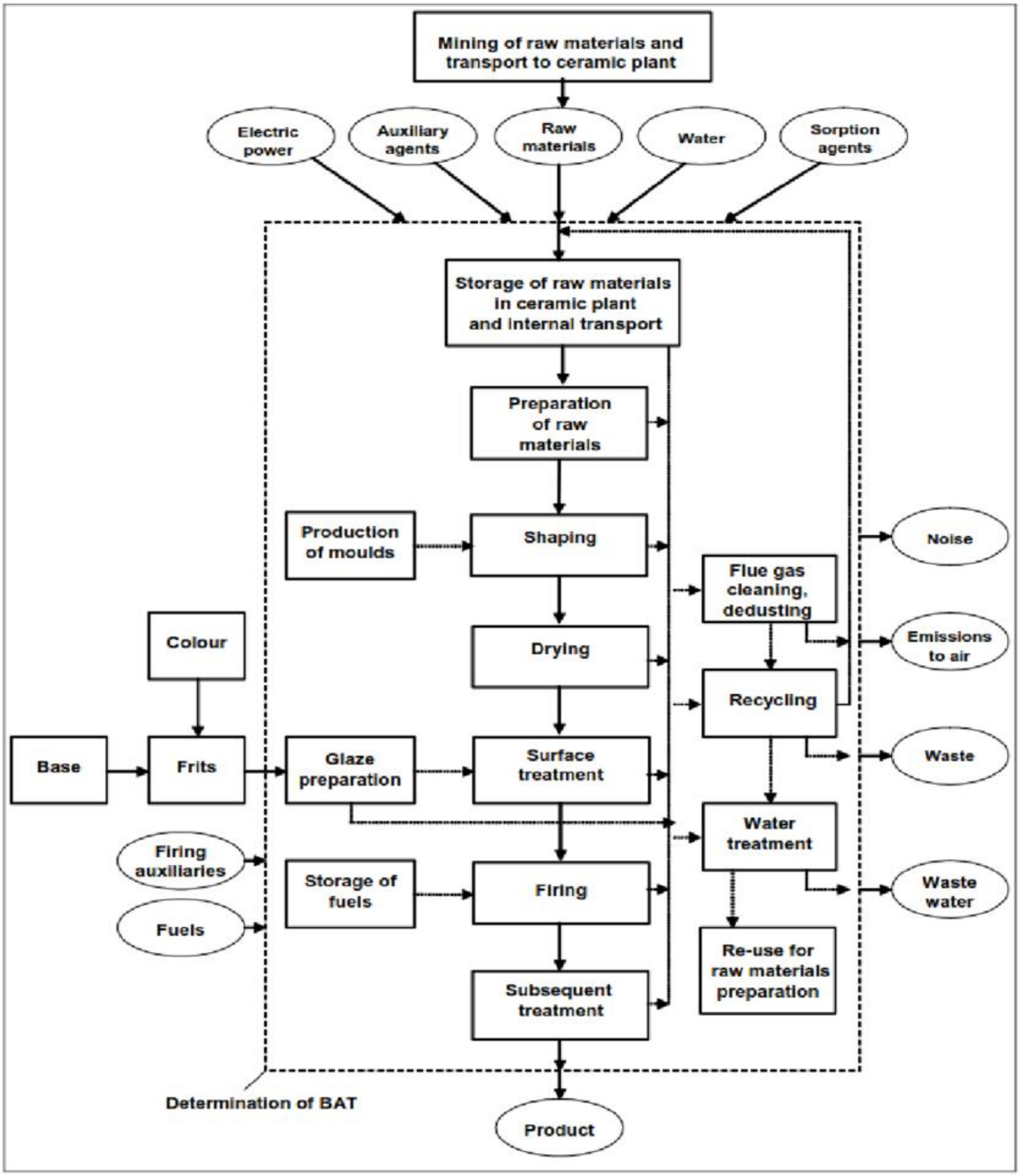

Figure 2.1: General ceramics manufacturing process (Salminen *et al*., 2019)

2.6 Heavy Metals in Industrial Effluents

Heavy metals are naturally occurring elements defined by their high atomic weights and densities exceeding 5 g/cm³ (Duffus, 2002). This group includes metals such as Pb, Cd, Hg, Cr, As, Cu, Zn, and Ni, which are frequently detected in industrial effluents. These metals possess distinct physicochemical properties that contribute to their environmental significance. Their high toxicity, even at low concentrations, poses severe risks to ecosystems and human health (Ali *et al*., 2019). Heavy metals are non-biodegradable, meaning they cannot be broken down by natural microbial or chemical processes, leading to their persistence in the environment (Tchounwou*et al*., 2012). This property allows them to accumulate in soils, sediments, and biota over time, amplifying their ecological impact.

The chemical behavior of heavy metals is influenced by their ability to form complexes with organic and inorganic ligands, which affects their solubility, mobility, and bioavailability (Nriagu, 1996). For example, metals like mercury can form organometallic compounds, such as methylmercury, which are highly bioavailable and toxic to organisms (Boening, 2000). Additionally, heavy metals often exist in multiple oxidation states (e.g., Cr(III) vs. Cr(VI)), which alters their reactivity and environmental fate (Shanker *et al*., 2005). Their metallic nature also enables them to participate in redox reactions, influencing their interactions with environmental matrices such as water and soil. These properties collectively make heavy metals a significant concern in industrial effluent management, as their persistence and toxicity can lead to long-term contamination of water bodies and food chains (Jaishankar *et al*., 2014).

2.7 Sources and Pathways of Heavy Metal Contamination

Heavy metal contamination in industrial effluents originates from a wide range of anthropogenic activities, each contributing distinct metals and varying concentrations to wastewater streams. Below is a detailed exploration of the primary sources:

2.7.1 Mining and Smelting

Mining operations, including the extraction of ores for metals like Cu, Pb, and Zn, generate significant quantities of heavy metal-laden effluents. Smelting processes, which involve heating ores to extract metals, release metals such as arsenic, cadmium, and lead into wastewater through slag and tailings (Wu *et al*., 2016). For instance, acid mine drainage, a byproduct of sulfide ore mining, is highly acidic and contains elevated levels of heavy metals, which can contaminate surface and groundwater (AkcilandKoldas, 2006).

2.7.2 Electroplating

The electroplating industry, used to coat metals for corrosion resistance or aesthetic purposes, is a major source of heavy metals like Cr, Ni, and Cd. The rinsing of plated materials generates effluents with high metal concentrations, often discharged directly into water bodies if treatment is inadequate (Barakat, 2013). Chromium, particularly in its hexavalent form, is a common pollutant from electroplating due to its use in chrome plating processes (Vardhan *et al*., 2019).

2.7.3 Battery Manufacturing

The production and disposal of batteries, especially lead-acid and Ni-Cd batteries, release Pb, Cd, and Hg into effluents. These metals are used in battery electrodes and electrolytes, and improper handling or disposal of spent batteries exacerbates contamination (MasindiandMuedi, 2018). Lead, in particular, is a significant concern due to its widespread use and high toxicity (Tchounwou*et al*., 2012).

2.7.4 Tanneries

Leather processing in tanneries relies heavily on chromium-based tanning agents, leading to effluents rich in Cr(III) and Cr(VI). Chromium is used to stabilize leather, but its discharge into water bodies poses severe environmental risks due to the high toxicity of Cr(VI) (Shanker *et al*., 2005). Tannery effluents are often poorly treated in developing regions, amplifying contamination (Vardhan *et al*., 2019).

2.7.5 Chemical and Pigment Manufacturing

The production of paints, dyes, and pigments frequently involves heavy metals such as Cd, Pb, and Hg as colorants or stabilizers. Wastewater from these industries contains residual metals from raw materials or chemical reactions, contributing to effluent contamination (Wu *et al*., 2016). For example, cadmium-based pigments used in yellow and red paints are a significant source of Cd pollution (Barakat, 2013).

2.7.6 Textile Industry

Textile manufacturing processes, particularly dyeing and finishing, introduce metals like copper, chromium, and Zn into effluents. These metals are used as mordants or in metal-complex dyes, and their release into wastewater is a growing concern in regions with intensive textile production (Jaishankar *et al*., 2014).

The pathways of heavy metal contamination are multifaceted, involving direct and indirect routes. Direct discharge of untreated or partially treated effluents into rivers, lakes, or seas is a primary pathway, particularly in regions with lax regulatory enforcement (MasindiandMuedi, 2018). Atmospheric deposition, where metals from industrial emissions settle into water bodies, is another significant route, especially for volatile metals like mercury (Nriagu, 1996). Surface runoff from contaminated sites, such as landfills or mine tailings, transports metals into aquatic systems, while leaching from soils or waste heaps contaminates groundwater (He *et al*., 2005). These pathways are interconnected, often involving multiple environmental compartments (soil, water, air), which complicates efforts to mitigate contamination (Jaishankar *et al*., 2014).

2.8 Behavior, Mobility, and Persistence of Heavy Metals in the Environment

The environmental behavior of heavy metals is governed by their chemical speciation, which determines their solubility, bioavailability, and toxicity (Bradshaw *et al*., 2013). Speciation refers to the different chemical forms (e.g., free ions, complexes, or precipitates) a metal can take, each with distinct environmental impacts. For instance, hexavalent chromium - Cr(VI) is highly soluble and mobile in water, making it more toxic and bioavailable than the less soluble trivalent chromium - Cr(III) (Shanker *et al*., 2005). Similarly, methylmercury, an organic form of mercury, is more bioaccumulative than inorganic mercury, posing greater risks to aquatic organisms and humans (Boening, 2000).

Heavy metals exhibit varying degrees of mobility in the environment, influenced by their interactions with environmental matrices. In aquatic systems, metals often adsorb onto sediments or particulate matter, reducing their mobility but increasing their persistence (Peng *et al*., 2009). This adsorption is governed by factors such as surface charge, particle size, and the presence of organic matter or clay minerals. For example, Pb and Cd strongly bind to organic matter, reducing their mobility in water but creating long-term reservoirs in sediments (Appelo and Postma, 2005). Conversely, metals like arsenic remain mobile under certain conditions, such as in alkaline or reducing environments, increasing their potential to contaminate groundwater (Nriagu, 1996).

The persistence of heavy metals is a critical concern due to their non-biodegradable nature. Unlike organic pollutants, heavy metals cannot be degraded by microbial or chemical processes, leading to their accumulation in environmental compartments over time (Tchounwou*et al.*, 2012). This persistence is exacerbated by processes like bioaccumulation, where metals accumulate in the tissues of organisms, and biomagnification, where concentrations increase through the food chain (Ali *et al.*, 2019). For example, Hg biomagnifies in aquatic food webs, reaching high concentrations in predatory fish, this poses risks to human health through consumption (Boening, 2000). Environmental factors such as pH, redox potential, and organic matter content further influence metal behavior. Low pH, for instance, increases the solubility of metals like Cd and Pb, enhancing their mobility and bioavailability, while high organic matter content can immobilize metals through chelation (Appelo and Postma, 2005).

2.9 Factors Influencing Heavy Metal Concentration in Effluents

The concentration of heavy metals in industrial effluents is determined by a complex interplay of factors, each contributing to the variability observed in wastewater streams. Below is a detailed analysis of these factors:

2.9.1 Type of Industrial Process

The nature of the industrial activity directly influences the types and concentrations of heavy metals in effluents. Processes like electroplating, which rely on metal solutions for coating, generate high concentrations of metals such as Cr, Ni, and Cd (Barakat, 2013). Similarly, mining and smelting produce effluents with metals like Pb, Zn, and As due to the processing of metal-rich ores (Wu *et al*., 2016). The specific technology or method used in these processes, such as the use of cyanide in gold mining, can further exacerbate metal release into wastewater (AkcilandKoldas, 2006).

2.9.2 Raw Materials Used

The composition of raw materials significantly affects heavy metal concentrations. For example, the use of lead-based compounds in battery manufacturing or chromium salts in tanneries directly contributes to high metal loads in effluents (Vardhan *et al*., 2019). Impurities in raw materials, such as trace metals in ores or chemicals, also add to the contamination. In pigment production, cadmium and lead are intentionally used for their coloring properties, leading to elevated concentrations in wastewater (Barakat, 2013).

2.9.3 Wastewater Treatment Efficiency

The presence and effectiveness of wastewater treatment systems play a critical role in determining heavy metal concentrations in effluents. Inadequate or absent treatment systems result in higher metal loads, as seen in many developing countries where regulatory enforcement is weak (MasindiandMuedi, 2018). Common treatment methods, such as chemical precipitation or ion exchange, can reduce metal concentrations, but their efficiency depends on proper design and operation. For instance, incomplete precipitation of metals like lead or chromium due to suboptimal pH conditions can lead to higher residual concentrations in treated effluents (Barakat, 2013).

2.9.4 Operational Conditions

Parameters such as temperature, pH, and redox conditions during industrial processes influence metal solubility and discharge levels. For example, acidic conditions in electroplating or mining effluents increase the solubility of metals like Cd and Zn, leading to higher concentrations in wastewater (Appelo and Postma, 2005). High temperatures in processes like smelting can enhance the dissolution of metals into effluents, while redox conditions affect the speciation of metals like chromium and arsenic (Shanker *et al*., 2005).

2.9.5 Seasonal Variations

Environmental factors, such as rainfall and temperature fluctuations, impact heavy metal concentrations in effluents. During rainy seasons, increased runoff can dilute metal concentrations in effluents but may also mobilize metals from contaminated sites, such as mine tailings, into water bodies (Wu *et al*., 2016). Conversely, dry seasons can concentrate metals in effluents due to reduced water volumes, increasing their environmental impact (MasindiandMuedi, 2018).

2.9.6 Regulatory and Management Practices

The enforcement of environmental regulations and the adoption of best management practices significantly affect heavy metal concentrations. In regions with stringent regulations, industries are more likely to implement advanced treatment technologies, reducing metal discharge (Barakat, 2013). However, in areas with lax oversight, untreated or poorly treated effluents are common, leading to higher metal concentrations (MasindiandMuedi, 2018). The adoption of cleaner production techniques, such as substituting hazardous metals with less toxic alternatives, can also reduce contamination (Vardhan *et al*., 2019).

2.10 Common Heavy Metals in Industrial Effluents

Heavy metals are among the most persistent and toxic pollutants found in industrial effluents. They are non-biodegradable and tend to accumulate in biological systems, causing severe ecological and health-related consequences (Vardhan *et al*., 2019). The presence of these metals in industrial wastewater arises from a wide range of processes, including metal plating, pigment production, mining, electroplating, fertilizer manufacture, and ceramic production. Once released into the environment, they can persist for decades, accumulating in sediments, soils, and biological tissues. The following subsections provide detailed insight into the major heavy metals commonly encountered in industrial effluents, their sources, toxicity mechanisms, and environmental implications.

2.10.1 Lead (Pb)

Lead is a dense, malleable, and corrosion-resistant metal that has been widely used in various industries such as battery manufacturing, paint production, ceramics, and ammunition. Its occurrence in industrial effluents is primarily associated with wastewater from smelting, mining, and pigment manufacturing processes. Although global regulations have reduced the use of leaded gasoline and lead-based paints, significant contamination persists, especially in developing countries where industrial wastewater treatment facilities are often inadequate (Jaishankar *et al.*, 2014).

Lead is a cumulative toxicant, capable of accumulating in human and animal tissues over time. It primarily affects the nervous system, kidneys, and reproductive organs. In children, lead exposure results in neurological impairments such as reduced IQ, behavioral problems, and cognitive deficits (Needleman, 2004). In adults, chronic exposure is linked to hypertension, renal dysfunction, and anemia due to inhibition of enzymes involved in heme synthesis (Flora *et al.*, 2012).

Environmentally, Pb poses a long-term risk as it does not biodegrade. It tends to adsorb onto sediments and soil particles, where it can persist for centuries (Tchounwou*et al.*, 2012). Through bioaccumulation, it enters the food chain, affecting aquatic organisms and higher trophic levels. Its persistence and toxicity classify it as a priority pollutant, warranting stringent control and remediation measures.

2.10.2 Cadmium (Cd)

Cadmium is a soft, bluish-white metal commonly released from industrial processes such as electroplating, Ni-Cd battery manufacturing, pigment production, and fertilizer industries. It is also a byproduct of Zn and Pb smelting (Godt *et al.*, 2006). Cadmium contamination of water bodies and soils often occurs through untreated or poorly treated industrial effluents.

Cadmium is recognized as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC, 2012). Chronic exposure can cause lung and prostate cancers, kidney damage, and bone demineralization. Cadmium disrupts calcium metabolism, resulting in skeletal deformities and osteoporosis—a phenomenon notably observed in the Itai-Itai disease outbreak in Japan (Nordberg *et al*., 2015). The biological half-life of Cd ranges between 10 and 30 years, allowing it to remain in the human body for extended periods, particularly in the kidneys and liver (JärupandÅkesson, 2009).

Environmentally, Cd is highly mobile in soils and aquatic systems, enhancing its bioavailability to plants and animals. It readily enters the food chain through crops grown on contaminated soils, posing significant risks to human health. Its persistence and potential to bioaccumulate make it a critical contaminant requiring strict environmental monitoring.

2.10.3 Chromium (Cr)

Chromium occurs naturally in several oxidation states, with trivalent chromium (Cr(III)) and hexavalent chromium (Cr(VI)) being the most environmentally significant. Chromium is extensively used in stainless steel production, leather tanning, pigment manufacture, and electroplating (Barnhart, 1997).

Cr(III) is an essential trace element required for glucose and lipid metabolism and is relatively non-toxic at low concentrations (Anderson, 1998). However, Cr(VI) is highly toxic, carcinogenic, and mutagenic. It is soluble in water and can readily penetrate biological membranes. Once inside the cell, Cr(VI) is reduced to Cr(III), generating reactive oxygen species (ROS) that damage DNA and cellular components (Zhitkovich, 2011).

Prolonged exposure to Cr(VI) has been linked to lung cancer, skin ulceration, and liver dysfunction (IARC, 2012). Industrial effluents from tanneries and electroplating facilities are major sources of Cr(VI) pollution. In aquatic environments, Cr(VI) is more mobile and bioavailable than Cr(III), but under reducing conditions, it can convert to the less toxic trivalent state. Effective treatment strategies—such as chemical reduction followed by precipitation—are therefore essential in minimizing Cr(VI) discharge from industrial sources.

2.10.4 Nickel (Ni)

Nickel is a silvery-white metal known for its corrosion resistance and strength. It is widely employed in electroplating, stainless steel manufacturing, and battery production, particularly in Ni-Cd and lithium-ion batteries (CempelandNikel, 2006). Industrial processes and mining activities release Ni compounds into effluents, contaminating both surface and groundwater.

Nickel serves as an essential trace element involved in enzymatic activities but becomes toxic when concentrations exceed physiological limits. Occupational exposure to Ni compounds through inhalation can cause respiratory diseases and nasal or lung cancer, leading to its classification as a Group 1 carcinogen (IARC, 2012). Skin contact with Ni can result in allergic dermatitis, a common occupational health issue (ThyssenandMenné, 2010). Ingestion through contaminated water or food may lead to gastrointestinal irritation, nephrotoxicity, and hepatotoxicity.

Environmentally, Ni solubility increases under acidic conditions, enhancing its uptake by plants and aquatic organisms. Its accumulation in the food chain can disrupt ecosystems and pose health risks to humans. Proper effluent management and pH control are therefore crucial to limit Ni mobility and bioavailability in industrial discharge.

2.10.5 Zinc (Zn)

Zinc is an essential micronutrient that plays vital roles in biological systems, including enzyme activation, immune response, and cell growth. However, excessive concentrations in industrial effluents can exert toxic effects on humans and the environment (NriaguandPacyna, 1988).

Zinc is commonly used in galvanization, pigment manufacturing, and fertilizer production. While Zn deficiency can cause growth retardation and immune dysfunction, overexposure results in nausea, vomiting, and interference with Cu metabolism, potentially leading to anemia (Prasad, 1995; Fosmire, 1990). In aquatic ecosystems, elevated Zn concentrations disrupt respiratory functions in fish and cause mortality among invertebrates (Eisler, 1993).

2.10.6 Copper (Cu)

Copper is also an essential micronutrient that plays critical roles during metabolism many in biological systems. It is utilized in electrical wiring, plumbing, and antifouling paints. It is essential for hemoglobin formation and enzymatic reactions but becomes harmful at high levels. Excessive Cu exposure can cause gastrointestinal distress, liver and kidney damage, and, in severe cases, symptoms similar to Wilson's disease (Brewer, 2010). In aquatic environments, Cu is highly toxic to algae and invertebrates, impairing photosynthesis and reproduction (Flemming and Trevors, 1989). Collectively, Zn and Cu contamination in industrial effluents highlights the dual challenge of maintaining essential micronutrient balance while preventing metal toxicity in ecosystems.

2.11 Environmental and Health Implications of Heavy Metal Contamination

Heavy metal contamination is a pressing global environmental issue with profound implications for ecosystems, food security, and public health. Heavy metals, including Pb, Cd, As, and Cr, are persistent, toxic, and capable of accumulating in environmental media and biological systems. Their non-biodegradable nature exacerbates their impact, as they remain in the environment for extended periods, posing long-term risks.

2.11.1 Impact on Soil and Water Quality

Heavy metals significantly impair the quality of soil and water, disrupting ecosystem functionality and human livelihoods. In soils, metals such as Cd, Pb, and Zn bind to soil particles, altering physicochemical properties like pH, organic matter content, and cation exchange capacity (Alloway, 2013). These changes reduce microbial diversity and activity, which are critical for nutrient cycling processes such as nitrogen fixation and organic matter decomposition (Wuana and Okieimen, 2011). For example, Cd contamination inhibits the activity of soil enzymes, leading to reduced soil fertility and lower crop yields, which can threaten agricultural productivity in affected regions (Nagajyoti *et al*., 2010). Furthermore, heavy metals can increase soil toxicity, making it unsuitable for certain plant species and reducing biodiversity in terrestrial ecosystems.

In aquatic environments, heavy metals enter water bodies through industrial discharges, mining effluents, agricultural runoff, and atmospheric deposition (Jaishankar *et al*., 2014). These contaminants accumulate in surface water, groundwater, and sediments, rendering water unsafe for drinking, irrigation, and industrial use. For instance, lead and mercury contamination in rivers can elevate concentrations beyond safe thresholds, disrupting aquatic ecosystems by causing declines in fish populations and other aquatic organisms (Tchounwou *et al*., 2012). Sediments act as sinks for heavy metals, releasing them back into the water column under changing environmental conditions, such as pH or redox shifts, perpetuating contamination cycles (Förstner and Wittmann, 2012). In coastal regions, heavy metal pollution affects mangrove ecosystems and coral reefs, reducing their resilience to other stressors like climate change (Rainbow, 2007). The degradation of soil and water quality not only compromises ecosystem services but also poses significant challenges to food and water security, particularly in developing nations where regulatory frameworks may be inadequate.

2.11.2 Bioaccumulation and Biomagnification in Food Chains

Heavy metals enter food chains through uptake by primary producers, such as plants and phytoplankton, leading to bioaccumulation, where concentrations increase within an organism over time (Ali *et al*., 2019). This process is driven by the metals' ability to bind to organic tissues, resisting excretion or degradation. For example, plants grown in contaminated soils absorb metals like Cd and Pb through their roots, incorporating them into edible parts such as leaves, grains, or fruits (Clemens, 2006). In aquatic systems, phytoplankton and algae absorb metals like mercury(Hg), which are then transferred to zooplankton and fish, initiating the food chain transfer (Driscoll *et al*., 2013).

Biomagnification amplifies these concentrations as metals move up trophic levels, resulting in significantly higher levels in top predators, including humans, birds, and large fish (Gray, 2002). Mercury, for instance, undergoes biomagnification in marine ecosystems, with predatory fish like tuna and swordfish exhibiting concentrations thousands of times higher than in ambient water (Morel *et al*., 1998). This process poses substantial risks to human populations consuming contaminated seafood, as well as to wildlife such as seabirds and marine mammals. In terrestrial ecosystems, biomagnification occurs in food chains involving herbivores and carnivores, with metals like Cd accumulating in the kidneys and livers of mammals, affecting both wildlife and livestock (Burger, 2008). The transfer of heavy metals through food chains not only threatens biodiversity but also amplifies human exposure, particularly in communities reliant on local agriculture or fisheries.

2.11.3 Toxicological and Physiological Effects on Humans and Animals

Heavy metal exposure induces a wide range of toxicological and physiological effects, with severity depending on the metal, exposure duration, and organism susceptibility. In humans, lead is particularly harmful to the nervous system, causing cognitive impairments, developmental delays in children, and behavioral disorders (Lidsky and Schneider, 2003). Chronic Pb exposure is also linked to cardiovascular diseases and kidney dysfunction (Navas-Acien*et al*., 2007). Cadmium, a known carcinogen, accumulates in the kidneys and bones, leading to renal failure and osteoporosis, with long-term exposure increasing risks of lung and prostate cancers (Järup, 2003). Mercury, especially in its organic form (methylmercury), targets the central nervous system, causing tremors, memory loss, and motor dysfunction, with prenatal exposure linked to developmental neurotoxicity (Clarkson and Magos, 2006). Arsenic(As) exposure through contaminated water or food is associated with skin lesions, cardiovascular diseases, and cancers of the skin, liver, and bladder (Smith *et al*., 2000).

In animals, heavy metal toxicity manifests as impaired reproduction, immune suppression, and organ damage. For example, Cd exposure in birds reduces eggshell thickness, lowering hatching success, while Pb poisoning in waterfowl causes anemia and neurological disorders (Burger, 2008). Aquatic organisms, such as fish, exhibit reduced growth rates and altered behavior due to Hg and

Cd exposure, affecting population dynamics (Eisler, 1987). Chronic exposure to low levels of heavy metals can lead to subclinical effects, such as oxidative stress and immune system weakening, which may not be immediately apparent but compromise long-term health and survival (Tchounwou *et al*., 2012). These effects highlight the need for early detection and intervention to mitigate the impacts of heavy metal exposure on both human and animal populations.

2.11.4 Case Studies of Heavy Metal Pollution

Heavy metal pollution has caused significant environmental and health crises worldwide, with notable examples in Nigeria and other countries. In Nigeria, the 2010 lead poisoning outbreak in Zamfara State is a stark illustration of the dangers of unregulated artisanal mining. Gold extraction processes released lead-contaminated dust and soil, affecting over 18,000 people, primarily children, with more than 400 deaths reported (Lo *et al*., 2012). Blood lead levels in affected children exceeded 65 µg/dL, far above the World Health Organization's threshold of 5 µg/dL, leading to severe neurological damage and developmental impairments (Dooyema *et al*., 2012). In the Niger Delta, oil exploration and spills have contaminated water bodies with Cd, Cr and Ni, impacting fish populations and the health of communities reliant on fishing and agriculture (Adewuyi and Olowu, 2012). These incidents underscore the challenges of weak regulatory enforcement and inadequate remediation in Nigeria.

Globally, the Minamata Bay disaster in Japan (1950s–1960s) remains a seminal case of mercury pollution. Industrial discharges of methylmercury into the bay contaminated fish and shellfish, leading to severe neurological disorders, known as Minamata disease, in thousands of residents (Harada, 1995). Symptoms included tremors, hearing loss, and brain damage, with congenital cases affecting newborns whose mothers consumed contaminated seafood. In Bangladesh, arsenic contamination of groundwater, driven by geological factors and exacerbated by anthropogenic activities, has affected millions, causing skin lesions, cancers, and cardiovascular diseases (Smith *et al*., 2000). The crisis, linked to tube wells installed for drinking water, highlights the intersection of natural and human-induced contamination. In China, Cd pollution from mining and industrial activities has contaminated rice fields, leading to widespread health concerns, including "itai-itai" disease, characterized by severe bone pain and kidney damage (Zhao *et al*., 2015). These case studies emphasize the global nature of heavy metal pollution and the urgent need for coordinated mitigation efforts.

2.12 Previous Studies on Heavy Metal Contamination in Industrial Effluents

Several studies have been conducted globally and within Nigeria to evaluate the extent of heavy metal contamination in industrial effluents, and their findings have revealed consistent patterns of environmental pollution and non-compliance with established discharge standards. Industrial effluents are known to contain varying concentrations of heavy metals such as Pb, Zn, Fe, Cr, Ni, Cd and Cu, depending on the type of industry and the processes involved. In most developing countries, including Nigeria, inadequate waste management systems and weak enforcement of environmental laws have exacerbated the problem of heavy metal pollution in both terrestrial and aquatic ecosystems (Oladimeji *et al*., 2024).

In Benin City, Akharame *et al*. (2017) assessed the concentrations of heavy metals in effluents from four major processing industries, namely a carbonated soft drink factory, a brewery, a glass manufacturing company, and a meat-processing plant. Their results revealed that the concentrations of Zn ranged between 1.90 and 2.11 mg/L, while Pb levels were about 0.03 mg/L in some effluents. These values were found to exceed the permissible limits set by the Federal

Ministry of Environment (FMEnv) and the World Health Organization (WHO), particularly for Zn and Pb. The study concluded that most industries in Benin City were not compliant with environmental standards, thereby contributing significantly to the degradation of nearby water bodies and soils.

Similarly, Ochu *et al*. (2025) carried out a detailed investigation of heavy metal concentrations in manufacturing and beverage industry effluents, including those from the Seven-Up bottling plant in Edo State. Their findings showed alarmingly high levels of metals such as Fe (6.68 mg/L), Ni (6.65 mg/L), Zn (5.65 mg/L), and Cr (4.53 mg/L), all of which exceeded the WHO and national regulatory limits. This study provided strong evidence that industrial activities within Benin City and its environs release significant amounts of toxic metals into the environment, posing ecological and health risks to communities relying on surface and groundwater sources for domestic use. The study therefore emphasized the urgent need for stricter monitoring, periodic environmental audits, and the enforcement of effluent treatment policies in industrial zones across Edo State.

Beyond Benin City, Lovelyn *et al*. (2014) examined food industry effluents in Onitsha, Anambra State, and found that the mean concentrations of all studied heavy metals exceeded the acceptable limits prescribed by the FMEnv. This result demonstrated that food-processing industries in Nigeria are also major contributors to heavy metal pollution, and the study reinforced the notion that industrial effluents across different sectors in Nigeria often exceed regulatory discharge limits. Such non-compliance highlights the widespread nature of industrial pollution and the need for improved waste treatment infrastructure across the country.

Comparative studies in other developing regions have also provided insights into the magnitude of heavy metal contamination associated with industrial effluents. For instance, Zinabu*et al*. (2018) evaluated effluents from various industrial zones in Kombolcha, Ethiopia, including tanneries, steel-processing plants, textile factories, and meat-processing industries. Their results indicated extremely high concentrations of heavy metals, particularly Cr and Zn. The tannery effluent contained chromium at median levels of approximately 26,600 μg/L, while Zn concentrations in the steel-processing effluent were around 155,750 μg/L. These concentrations were many times higher than the permissible discharge limits, confirming that metal-intensive industries such as tanneries and steel plants are major point sources of heavy metal pollution.

A study conducted in Bangladesh on textile industry effluents similarly revealed significant contamination, with iron concentrations ranging from 0.14 to 6.85 mg/L (mean ~2.75 mg/L), Cr between 0.5 and 4.57 mg/L, Cd between 0.09 and 3.17 mg/L, and Pb between 0.07 and 1.12 mg/L. Although the textile industry is not primarily metal-based, the study highlighted that dyeing, bleaching, and other processing steps often introduce heavy metals into wastewater streams. This underscores the global nature of industrial effluent contamination and the importance of developing context-specific treatment strategies (Oladimeji *et al*., 2024).

Overall, these studies reveal that industrial effluents in Nigeria and elsewhere are major contributors to heavy metal pollution. The consistent exceedance of permissible discharge limits across different industrial sectors points to the urgent need for effective environmental management practices, regular effluent monitoring, and enforcement of pollution control measures. For Benin City in particular, the findings of Akharame *et al*. (2017) and Ochu *et al*. (2025) provide clear evidence that industrial waste management remains inadequate, thereby justifying the need for further research on specific sectors such as the ceramic industry, which is known to involve heavy-metal-based raw materials and glazes.

2.12.1 Studies Related to the Ceramic Industry and Heavy Metal Contamination

The ceramic industry is one of the most important but also one of the most environmentally challenging sectors due to its use of heavy metals in pigments, glazes, and raw materials. Several studies have investigated the extent to which ceramic manufacturing activities contribute to environmental contamination, both through direct effluent discharge and indirect pathways such as leaching and atmospheric deposition.

Joseph *et al*. (2019) carried out a study on soil and crop samples collected around the West African Ceramic Industry located in Oguro village, Ajaokuta Local Government Area, Kogi State, Nigeria. Although the concentrations of heavy metals in the soil samples were found to be below international permissible limits, the crop samples—particularly maize, sweet potato, and spinach—showed elevated levels of lead (Pb), exceeding recommended limits. The order of metal accumulation in the crops was Cu > Pb > Ni > Cr > Cd. This finding suggested that while the soil might not immediately appear contaminated, the bioaccumulation of metals in plants cultivated in proximity to the ceramic plant poses a potential risk to food safety and human health. The study demonstrated that emissions and particulate matter from ceramic operations could result in the transfer of heavy metals into the food chain through crop absorption.

Aderemi *et al*. (2017) investigated the leaching of heavy metals from ceramic food wares commonly sold in Nigeria, with emphasis on the glazes used during production. The study found high levels of heavy metals such as Pb (26.45–2071.46 µg/g), Cd (5.20–547 µg/g), Zn (1.24–

2681.02 µg/g) and As (2590–8848.4 µg/g), alongside traces of Cu, Cr, and Mn in some samples. Although this study did not directly measure effluent composition, it provided clear evidence that ceramic manufacturing processes in Nigeria rely heavily on heavy-metal-based compounds. Consequently, waste streams, wash waters, and effluents from such manufacturing plants are likely to contain these toxic metals. The study thus highlighted the potential of ceramic factories to contribute to environmental pollution through improper disposal of process residues and glaze-contaminated wastewater.

Furthermore, Shurygin *et al*. (2021) conducted a study in Europe to evaluate the treatment of ceramic industry wastewater using ceramic membrane technology. Their findings revealed that effluents from ceramic industries contained not only organic compounds but also significant levels of heavy metals. The researchers recommended advanced nanofiltration and membrane-based technologies for effective effluent treatment. This study underscored the treatment challenges associated with ceramic industry wastewater and confirmed that heavy-metal contamination is an inherent characteristic of ceramic manufacturing, regardless of geographic location.

Collectively, the reviewed studies demonstrate that heavy metal contamination is a common and recurring issue in industrial effluents globally, with the ceramic industry being a particularly relevant case due to its reliance on metal-based raw materials and colorants. In Nigeria, existing studies (Joseph *et al*., 2019; Aderemi *et al*., 2017) confirm that the ceramic industry contributes to environmental metal loading, with potential implications for soil fertility, water quality, and human health. The presence of Pb, Cd and Zn in ceramic-related environments suggests a need for continuous monitoring, the implementation of sustainable waste treatment technologies, and stricter environmental regulations to mitigate the risks associated with heavy metal exposure.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study Area

The study was conducted at a ceramic industry located in Utesi, within the Ikpoba-Okha Local Government Area (LGA) of Edo State, Nigeria. Ikpoba-Okha LGA is situated in the southern part of Edo State, approximately 10 km south of Benin City, the state capital. The coordinates of the study site are approximately 6°12'27" North and 5°40'56" East, situated in the southern part of Nigeria. The region forms part of the Niger Delta, an area renowned for its extensive wetlands, high biodiversity, and diverse industrial activities, including oil and gas exploration and ceramic production. The ceramic industry, a major manufacturing facility producing tiles and sanitary wares, discharges its industrial effluent into an open pond adjacent to the factory premises. This effluent pond serves as the primary point source of potential heavy metal contamination into the surrounding environment, including nearby streams and groundwater systems that support local communities for domestic and agricultural uses.

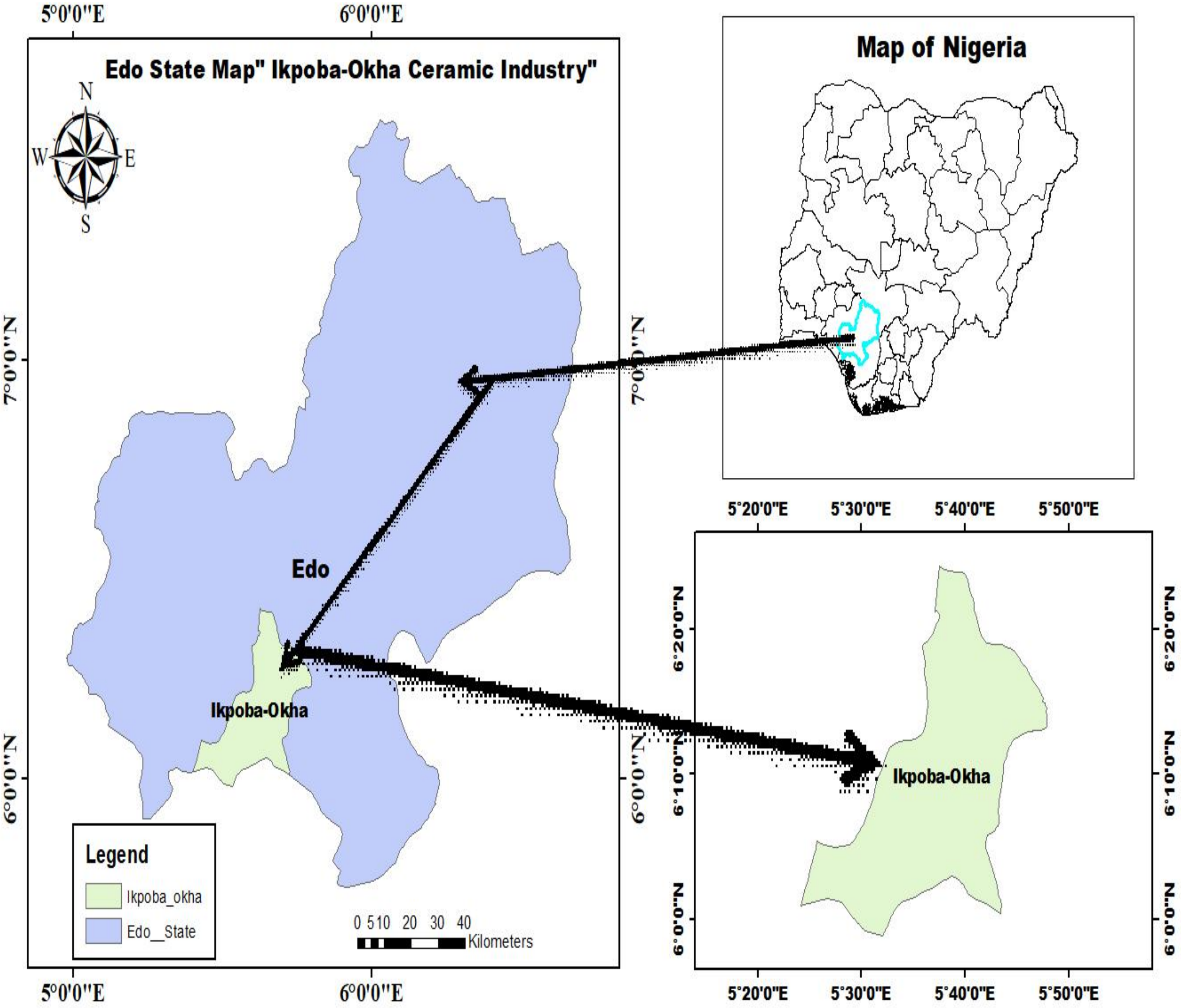

Figure 3.1: Map of the study area showing the sampling points

3.2 Sample Collection

A total of nine water samples were collected from three distinct points around the effluent discharge pond of the factory. Sampling was conducted three times over a period of three months (June, July, andAugust), corresponding to the rainy season when surface runoff and leaching are most pronounced. Water samples were collected in two-litre pre-cleaned plastic containers. Before sampling, the containers were rinsed three times with the water from the sampling point to prevent cross-contamination. Samples were properly labelled according to the sampling points and dates of collection. After collection, samples were stored at room temperature (approximately 25°C) and transported to the Master's Laboratory, Department of Chemistry, University of Benin, for further analysis (APHA, 2017).

3.3 Determination of Heavy Metal Concentrations

The concentrations of selected heavy metals Pb, Cd, Cr, Ni, Zn and Cu were determined using Atomic Absorption Spectrophotometry (AAS) after digestion of the effluent samples(AOAC, 1984).

3.4 Heavy Metal Analysis

3.4.1 Target Metals

The study targeted nine heavy metals commonly associated with ceramic industry effluents due to their use in glaze materials, pigments, and clay processing: Pb, Cd, Cr, Ni, Cu, Zn, Fe, Mn and As. These metals were selected based on their environmental persistence and potential health implications.

3.4.2 Sample Digestion

For heavy metal analysis, 100 mL portions of the acidified samples were digested following the USEPA Method 3010A (USEPA, 2004). Each sample was mixed with 5 mL of concentrated nitric acid and heated to 85°C until the volume was reduced to about 20 mL. Another 5 mL of nitric acid was added, and heating continued until approximately 5 mL remained. The digested samples were cooled, filtered through Whatman No. 42 filter paper, and diluted to 50 mL with deionized water. The digests were then stored at 4°C and analyzed within 72 hours.

3.4.3 Instrumentation and Quantification

Heavy metal concentrations were determined using a PerkinElmer Analyst 400 Atomic Absorption Spectrophotometer (AAS) (AOAC, 1984). The instrument was calibrated for each metal using multi-element standard solution (Merck Certipur, 0–100 µg/L) with correlation coefficients above 0.995. Analytical parameters, including wavelength, slit width, and detection limits, followed the manufacturer's specifications. Quality control measures included analysis of reagent blanks, duplicate samples (10%), and a certified reference material (NIST SRM 1643e) to verify accuracy and precision.

3.5 Health Risk Assessment

Health risk assessment (HRA) is a systematic approach used to estimate the likelihood and severity of adverse health effects that may result from exposure to environmental contaminants. In this study, the assessment was carried out to evaluate the potential non-carcinogenic and carcinogenic risks associated with heavy metal concentrations detected in the effluent samples collected from

Utesi. The procedure was adopted in line with the methods described by Bempah and Ewusi (2016), Wongsasuluk*et al*. (2014), and Eze *et al*. (2021).

The risk assessment process involved estimating the probable occurrence and potential health impact of the identified contaminants over a specific exposure period for both adults and children. The health risk was characterized into two main categories — non-carcinogenic and carcinogenic effects — based on the toxicity and exposure potential of each heavy metal.

3.5.1. Non-Carcinogenic Risk Assessment

The non-carcinogenic risk was determined by calculating the Hazard Quotient (HQ) for each heavy metal, using the equation:

$$\mathrm{HQ} = \frac{\mathrm{DI}}{RfD}$$

Where:

- *DI* is the estimated daily intake (mg/kg/day), and
- *RfD* is the oral reference dose (mg/kg/day), representing the maximum acceptable exposure level without appreciable health risk.

The Hazard Index (HI), which indicates the overall potential risk from combined exposure to multiple metals, was computed as the sum of all HQ values:

$$\mathrm{HI}=\mathrm{HQ}$$

An HQ or HI value greater than one ($HQ > 1$ or $HI > 1$) indicates a potential health concern, suggesting that exposure may pose non-carcinogenic risks to human health.

3.5.2. Carcinogenic Risk Assessment

The carcinogenic risk (CR) was estimated to evaluate the lifetime probability of an individual developing cancer due to exposure to carcinogenic metals. The CR was calculated using the equation:

$$CR=DI\times SF$$

Where:

- *DI* is the estimated daily intake (mg/kg/day), and
- *SF* is the slope factor $(\text{mg/kg/day})^{-1}$, which converts the average daily exposure to an incremental lifetime cancer risk.

The slope factors for the respective heavy metals were obtained from the United States Environmental Protection Agency Integrated Risk Information System (US EPA IRIS, 2004). According to the US EPA (1989, 2007) guidelines, acceptable carcinogenic risk levels typically range between 1×10^{-6} and 1×10^{-4}, representing one in a million to one in ten thousand lifetime cancer risks, respectively.

3.7 Data Analysis

The concentration of metals obtained from the AAS readings was expressed in mg/L. Data were statistically analyzed using Microsoft Excel 2021, where descriptive statistics such as mean, standard deviation, and range were computed. The results were compared with the World Health Organization (WHO, 2021) and Federal Ministry of Environment (FMEnv, 2011) permissible limits for drinking and surface water to assess potential health risks.

CHAPTER FOUR

4.0 RESULTS

The result of the analysis for June is presented in Table 4.1. The findings revealed that Cr recorded the highest concentration among the analyzed metals, ranging from 0.97 ± 0.06 mg/L in Utesi C to 1.00 ± 0.00 mg/L in both Utesi A and Utesi B. This was followed by Pb, which had values between 0.27 ± 0.06 mg/L and 0.47 ± 0.06 mg/L across the sampling points. Copper concentrations ranged from 0.10 ± 0.00 mg/L in Utesi A to 0.27 ± 0.06 mg/L in Utesi C, while Mn appeared in low concentrations (0.10–0.17 mg/L). Nickel and Cd were not detected (ND) in any of the samples during this month.

The result of the analysis for July is presented in Table 4.2. During this period, Mn recorded the highest concentration among the metals, ranging from 1.07 ± 0.06 mg/L in Utesi C to 3.00 ± 0.10 mg/L in Utesi A. This was followed by Cu, which ranged between 0.10 ± 0.00 mg/L and 0.57 ± 0.06 mg/L, with the highest concentration observed in Utesi C. Lead levels were relatively moderate, ranging from 0.10 ± 0.00 mg/L to 0.20 ± 0.00 mg/L. Nickel was only detected in Utesi B at 0.17 ± 0.06 mg/L, while Cr and Cd were not detected in any of the samples.

The result of the analysis for August is presented in Table 4.3. During this month, Cu recorded the highest concentration, ranging from 0.17 ± 0.12 mg/L in Utesi A to 0.27 ± 0.06 mg/L in Utesi C. Chromium was also detected in measurable quantities, ranging from 0.10 ± 0.00 mg/L to 0.27 ± 0.06 mg/L. Lead concentrations were moderate (0.27–0.37 mg/L), while Mn appeared in low levels (0.20 ± 0.00 mg/L only in Utesi B). Notably, Cd, which had not been detected in the previous months, was present in Utesi A and Utesi C with concentrations of 0.03 ± 0.06 mg/L and 0.63 ± 0.12 mg/L, respectively. Nickel (Ni) remained undetected across all sampling sites.

The average concentrations of heavy metals across the three months are presented in Figure 4.1. The overall mean values show that Mn had the highest concentration (1.10 mg/L), followed by Cr at 0.58 mg/L, Pb at 0.27 mg/L, Cu at 0.24 mg/L, Cd at 0.22 mg/L, and Ni at 0.06 mg/L.

Table 4.1: Mean Concentrations (mg/L) of Heavy Metals in Effluent Samples Collected in June

Sample Code	Cu (mg/L)	Cr (mg/L)	Ni (mg/L)	Pb (mg/L)	Mn (mg/L)	Cd (mg/L)
Utesi A	0.10 ± 0.00	1.00 ± 0.00	ND	0.27 ± 0.06	ND	ND
Utesi B	0.13 ± 0.06	1.00 ± 0.00	ND	0.27 ± 0.06	0.17 ± 0.06	ND
Utesi C	0.27 ± 0.06	0.97 ± 0.06	ND	0.47 ± 0.06	0.10 ± 0.00	ND

Values represented in mean ± standard deviation

Keys:

ND = Not Detected

Table 4.2: Mean Concentrations (mg/L) of Heavy Metals in Effluent Samples Collected in July

Sample Code	Cu (mg/L)	Cr (mg/L)	Ni (mg/L)	Pb (mg/L)	Mn (mg/L)	Cd (mg/L)
Utesi A	0.10 ± 0.00	ND	ND	0.13 ± 0.06	3.00 ± 0.10	ND
Utesi B	0.27 ± 0.15	ND	0.17 ± 0.06	0.20 ± 0.00	2.07 ± 0.06	ND
Utesi C	0.57 ± 0.06	ND	ND	0.10 ± 0.00	1.07 ± 0.06	ND

Values represented in mean ± standard deviation

Keys:

ND = Not Detected

Table 4.3: Mean Concentrations (mg/L) of Heavy Metals in Effluent Samples Collected in August

Sample Code	Cu (mg/L)	Cr (mg/L)	Ni (mg/L)	Pb (mg/L)	Mn (mg/L)	Cd (mg/L)
Utesi A	0.17 ± 0.12	0.17 ± 0.12	ND	0.37 ± 0.12	ND	0.03 ± 0.06
Utesi B	0.23 ± 0.06	0.27 ± 0.06	ND	0.33 ± 0.06	0.20 ± 0.00	ND
Utesi C	0.27 ± 0.06	0.10 ± 0.00	ND	0.27 ± 0.06	ND	0.63 ± 0.12

Values represented in mean ± standard deviation

Keys:

ND = Not Detected

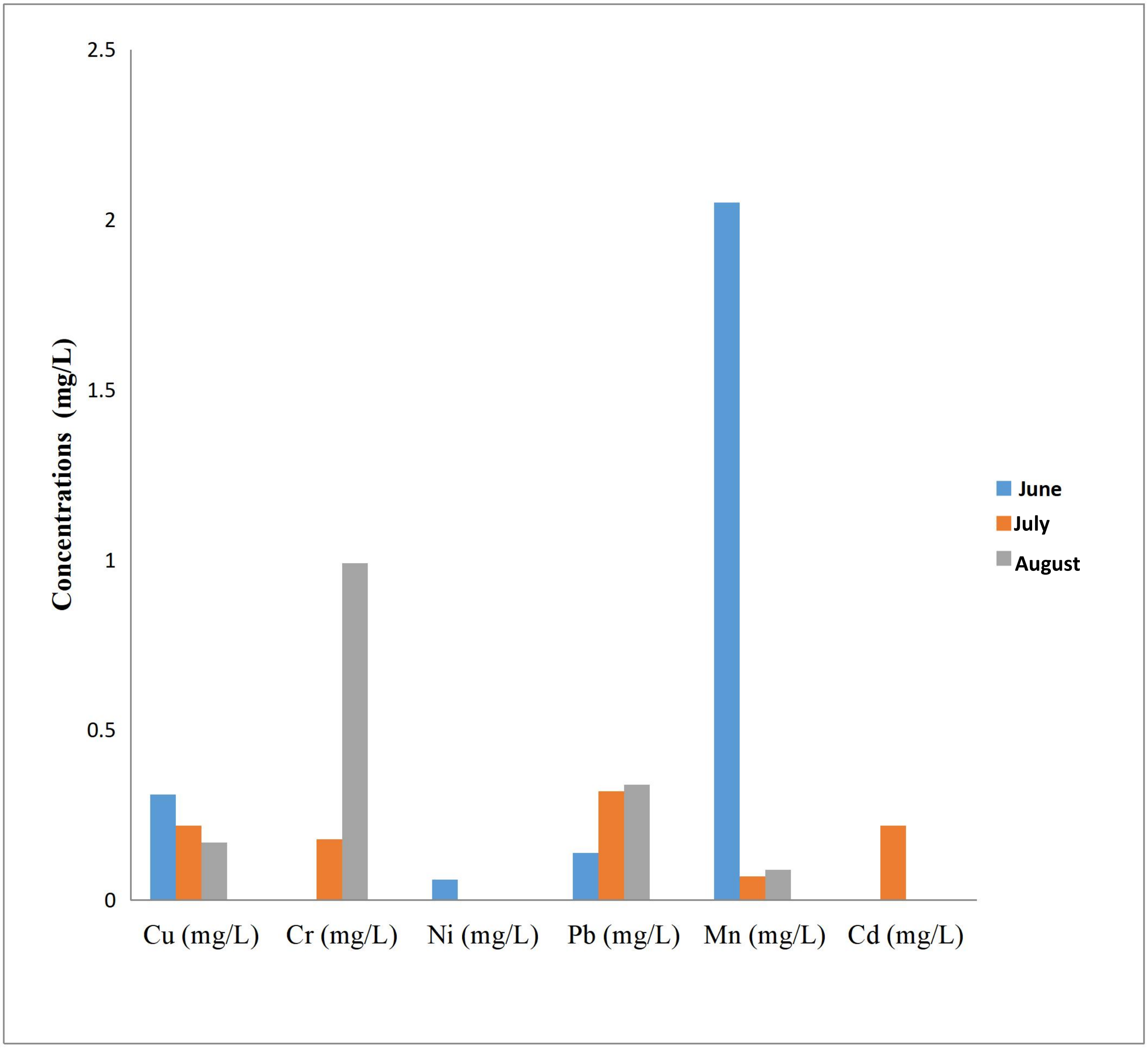

Figure 4.1: Average concentrations of heavy across all sampling sites for June, July, and August

The comparison between measured concentrations and regulatory standards is presented in Table 4.4. The findings reveal that while Cu concentrations were within both WHO (2.0 mg/L) and NESREA (1.0 mg/L) limits, Cr, Ni, Pb, Mn and Cd exceeded one or both permissible thresholds. Lead levels (0.10–0.47 mg/L) exceeded the WHO limit of 0.01 mg/L and the NESREA limit of 0.05 mg/L, indicating significant contamination. Manganese (0.10–3.00 mg/L) also exceeded acceptable limits (WHO: 0.5 mg/L; NESREA: 0.2 mg/L). Cadmium (up to 0.63 mg/L) far surpassed the limits of 0.003 mg/L (WHO) and 0.01 mg/L (NESREA).

The result used for health risk calculation is presented in Table 4.5. The metals were arranged in descending order of mean concentration as follows: Mn (1.10 mg/L) > Cr (0.58 mg/L) > Pb (0.27 mg/L) > Cu (0.24 mg/L) > Cd (0.22 mg/L) > Ni (0.06 mg/L). These values were used to evaluate non-carcinogenic and carcinogenic health risks.

The non-carcinogenic health risk assessment results are presented in Table 4.6. The hazard quotient (HQ) values for adults and children indicate that Cd had the highest potential risk (HQ: 0.18 for adults and 0.43 for children), followed by Cr and Pb. Copper and Mn posed minimal risks. The overall hazard index (HI) values were 0.36 for adults and 0.86 for children, both below the threshold value of 1.

The result of the carcinogenic risk assessment is presented in Table 4.7. Among the metals assessed, Cd exhibited the highest carcinogenic risk, with CR values of 1.10×10^{-4} for adults and 2.62×10^{-4} for children, both exceeding the acceptable risk threshold (10^{-6} to 10^{-4}). Chromium and Pb had CR values within acceptable limits, indicating lower carcinogenic potential.

Table 4.4: Comparison of Mean Heavy Metal Concentrations in Effluent Samples with WHO (2017) and NESREA (2011) Permissible Limits

Metal	Mean Range (mg/L)	WHO Limit (mg/L)	NESREA Limit (mg/L)	Compliance Status
Cu	0.10 – 0.57	2.0	1.0	Within limit
Cr	0.10 – 1.00	2.0	0.5	Exceeds NESREA limit
Ni	ND – 0.17	0.02	0.05	Slightly exceeds the WHO limit
Pb	0.10 – 0.47	0.01	0.05	Exceeds both limits
Mn	0.10 – 3.00	0.5	0.2	Exceeds both limits
Cd	ND – 0.63	0.003	0.01	Exceeds both limits

Table 4.5: Mean Heavy Metal Concentrations Used for Health Risk Calculation (mg/L)

Metal	**Mean Concentration (mg/L)**
Cu	0.24
Cr	0.58
Ni	0.06
Pb	0.27
Mn	1.10
Cd	0.22

Table 4.6: Non-Carcinogenic Risk (HQ) and Hazard Index (HI)

Metal	**RfD (mg/kg/day)**	**HQ (Adults)**	**HQ (Children)**
Cu	0.04	0.0021	0.0049
Cr	0.003	0.0893	0.211
Pb	0.0035	0.078	0.185
Mn	0.14	0.0079	0.018
Cd	0.001	0.18	0.43
HI (ΣHQ)		**0.36**	**0.86**

HI values < 1 indicate no significant non-carcinogenic health risk.

Table 4.7: Carcinogenic Risk (CR) of Selected Heavy Metals

Potentially toxic elements	**Slope Factor (SF)**	**CR (Adults)**	**CR (Children)**	**Risk Level**
Pb	0.0085	1.82×10^{-7}	4.31×10^{-7}	Acceptable
Cd	6.1	1.10×10^{-4}	2.62×10^{-4}	High
Cr	0.5	2.23×10^{-5}	5.27×10^{-5}	Acceptable

CHAPTER FIVE

5.0 DISCUSSION

Industrial effluents from ceramic industries represent a significant environmental concern due to their complex composition, which often includes heavy metals such as Pb, Cd, Cr, Ni and Mn. These metals originate from various stages of production, including glazing, coloring, and firing processes that involve metal oxides and pigments (Aderemi *et al*., 2017; Joseph *et al*., 2019). Without adequate treatment, the discharge of these effluents into surrounding water bodies and soils can result in long-term ecological degradation and pose serious health risks to local populations. In developing regions such as Nigeria, weak enforcement of environmental regulations and inadequate industrial wastewater management exacerbate the contamination of surface and groundwater resources (Oladimeji *et al*., 2024).

The present study assessed the concentration of heavy metals in effluents discharged from a ceramic industry in Benin City, Edo State, Nigeria, and evaluated the associated potential health risks. The results revealed variable levels of contamination across the sampling months of June, July, and August. In June, Cr recorded the highest concentration among the analyzed metals, reaching 1.00 mg/L, followed by Pb at 0.47 mg/L. Copper concentrations ranged between 0.10–0.27 mg/L, while Mn appeared only in trace amounts (0.10–0.17 mg/L). Nickel and Cd were not detected (ND) in any of the samples during this month. By July, Mn recorded the highest concentration (1.07–3.00 mg/L), followed by Cu (0.10–0.57 mg/L) and Pb (0.10–0.20 mg/L), while Cr, Ni, and Cd were not detected. By August, Cu remained the dominant metal, with concentrations ranging from 0.17–0.27 mg/L, but Cd emerged at a high concentration of 0.63 mg/L, and both Pb and Cr levels also increased (0.27–0.37 mg/L and 0.10–0.27 mg/L, respectively). The overall mean concentrations followed the order Mn > Cr > Pb > Cu > Cd > Ni, indicating that manganese and chromium were the most prevalent contaminants in the effluent samples across the study period.

Comparison with regulatory limits revealed that while Cu concentrations were within the permissible thresholds of both WHO (2017) and NESREA (2011), Cr, Ni, Pb, Mn and Cd exceeded one or both permissible standards. Lead levels (0.10–0.47 mg/L) surpassed the WHO limit of 0.01 mg/L and the NESREA limit of 0.05 mg/L, confirming significant contamination. Similarly, Mn (0.10–3.00 mg/L) and Cd (up to 0.63 mg/L) were above acceptable limits. These findings suggest that the ceramic industry in Benin City contributes to elevated heavy metal pollution, reflecting similar trends observed in other Nigerian industrial zones (Akharame *et al*., 2017; Ochu *et al*., 2025).

The results of this study are consistent with previous reports that identified industrial effluents as major sources of heavy metal pollution in Benin City and other parts of Nigeria. According to Ekhaise and Anyasi (2011), effluents discharged into the Ikpoba River from various industrial sources—including rubber processing, breweries, and metal works—contained high concentrations of heavy metals such as Pb and Cd, rendering the water unsafe for domestic use. Similarly, Akharame *et al*. (2017) found that effluents from major industries in Benin City contained Zn (1.90–2.11 mg/L) and Pb (0.03 mg/L) levels exceeding regulatory standards. Ochu *et al*. (2025) also reported that effluents from beverage and manufacturing plants in Edo State contained Fe (6.68 mg/L), Ni (6.65 mg/L), and Cr (4.53 mg/L), far above permissible limits. The high concentrations of Mn, Cr, and Cd observed in the current study mirror these findings and further affirm that industrial discharges in Benin City represent a significant environmental risk.

The contamination observed in this study is also comparable to findings from similar investigations conducted on ceramic industries in Nigeria and abroad. Aderemi *et al*. (2017) detected high levels of Pb (26.45–2071.46 µg/g) and Cd (5.20–547 µg/g) in ceramic food wares produced locally, highlighting the heavy-metal dependence of ceramic manufacturing processes. Likewise, Joseph *et al*. (2019) reported that soil and crop samples collected around a ceramic industry in Ajaokuta, Kogi State, contained elevated levels of Pb and Cu, indicating atmospheric and effluent-mediated transfer of metals into the environment. These studies support the current finding that ceramic operations in Benin City likely release metal-rich effluents that pose contamination risks to surrounding ecosystems.

Globally, studies have also demonstrated that ceramic industries contribute substantially to heavy metal pollution. Shurygin *et al*. (2021) found that effluents from European ceramic plants contained significant levels of Cr and Mn, necessitating the adoption of advanced membrane filtration systems for effective treatment. This aligns with the present study's observation that untreated ceramic effluents in Benin City contain toxic metal concentrations that exceed environmental safety limits.

The high levels of Pb, Cd, and Mn detected in the effluent samples raise critical environmental and public health concerns. Lead and cadmium are known neurotoxic and carcinogenic elements that can accumulate in aquatic and terrestrial organisms, leading to biomagnification across food chains (Dooyema *et al*., 2012; Adewuyi and Olowu, 2012). The health risk assessment in this study revealed that cadmium posed the highest non-carcinogenic (HQ = 0.18 for adults; 0.43 for children) and carcinogenic risk (CR = 1.10×10^{-4} for adults; 2.62×10^{-4} for children), exceeding the acceptable risk threshold. Children were found to be more vulnerable due to higher exposure rates relative to body weight.

Similar health implications have been reported in other regions. For example, the lead poisoning outbreak in Zamfara State, Nigeria, caused by artisanal mining, resulted in elevated blood lead levels above 65 µg/dL among children, leading to neurological damage and fatalities (Lo *et al*., 2012; Dooyema *et al*., 2012). Likewise, the Minamata Bay incident in Japan, where industrial discharges of methylmercury caused severe neurological disorders, exemplifies the global impact of unregulated heavy metal pollution (Harada, 1995). The presence of carcinogenic metals such as cadmium and chromium in the ceramic effluents analyzed in this study suggests a potential for similar long-term health hazards if mitigation measures are not implemented.

The findings of this study underscore the urgent need for strengthened environmental monitoring and enforcement mechanisms in industrial zones across Benin City. Despite existing environmental regulations by NESREA and the Federal Ministry of Environment (FMEnv), non-compliance persists, largely due to inadequate effluent treatment infrastructure and a lack of regular inspections. As recommended by Ochu *et al*. (2025), industries should be mandated to conduct periodic environmental audits and adopt cleaner production technologies; including the use of advanced effluent treatment systems such as membrane filtration (Shurygin *et al*., 2021).

Public awareness campaigns should also be intensified to educate communities on the dangers of using contaminated water sources. In addition, the implementation of phytoremediation and bioremediation strategies may provide cost-effective and sustainable options for mitigating metal contamination in affected areas.

5.1 Recommendations

Based on the literature reviewed, the following recommendations are made to address the persistent problem of heavy metal contamination in industrial effluents:

1. **Strengthen Environmental Regulations and Enforcement:** The Federal Ministry of Environment (FMEnv) and the National Environmental Standards and Regulations Enforcement Agency (NESREA) should intensify monitoring and enforcement of effluent discharge standards. Industries operating in Benin City and elsewhere in Nigeria should be required to obtain regular environmental compliance certifications backed by periodic inspections.
2. **Implementation of Effective Effluent Treatment Technologies:** Industries should adopt modern treatment technologies such as membrane filtration, nanofiltration, and phytoremediation to remove heavy metals from wastewater before discharge.
3. **Promotion of Cleaner Production Techniques:** Industries, especially in the ceramic, textile, and beverage sectors, should prioritize cleaner production processes that minimize the use of heavy-metal-based compounds. Substitution with eco-friendly raw materials and glazes should be encouraged through government incentives and technical support.
4. **Periodic Environmental Audits:** Regular audits should be made mandatory for all industrial facilities to ensure compliance with environmental standards. These audits will also help track the efficiency of waste management systems and guide the implementation of corrective measures.
5. **Public Health Surveillance and Community Awareness:** Communities living near industrial zones should be sensitized about the risks of heavy metal exposure through contaminated water and soil. Health surveillance programs should be established to

monitor potential toxicological effects, particularly in vulnerable groups such as children and pregnant women.

6. **Research and Data Management:** Further research should be conducted to provide updated data on the levels and trends of heavy metal contamination in different industrial sectors, especially in Benin City and the broader Edo State. Universities and research institutions should collaborate with industries to develop innovative, low-cost treatment methods suited to local conditions.
7. **Adoption of Integrated Pollution Management Policies:** A coordinated "One Environment"approach linking industrial regulation, environmental monitoring, and public health should be adopted at the state and national levels. This will ensure that pollution control strategies are comprehensive, data-driven, and sustainable

5.2 Conclusion

The assessment of heavy metal concentrations in effluents from the ceramic industry in Benin City revealed that Mn, Cr, Pb, and Cd were present at levels exceeding international and national safety limits. The associated health risk analysis demonstrated that cadmium poses the greatest potential hazard, particularly to children. These findings corroborate previous reports on industrial pollution in Benin City and highlight the contribution of ceramic manufacturing to heavy metal contamination in the environment. Effective regulatory enforcement, improved wastewater treatment technologies, and continuous monitoring are therefore essential to safeguard public health and maintain environmental integrity.

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APPENDIX

Plate 1: Effluent Discharge point of the Industry in June

Plate 2: Effluent Discharge point of the Industry in July

Plate 3: Effluent Discharge point of the Industry in August