ASSESSMENT OF ACTIVATED CARBON TREATMENT EFFICIENCY ON COPPER NITRATE-CONTAMINATED BOREHOLE WATER FOR DOMESTIC AND IRRIGATION PURPOSE

BY

ABUAH IKECHUKWU VALENTINE
ENG2008265

A PROJECT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF BACHELOR OF CIVIL ENGINEERING (B.ENG) DEGREE

IN

THE DEPARTMENT OF CIVIL ENGINEERING, FACULTY OF ENGINEERING, UNIVERSITY OF BENIN, NIGERIA.

NOVEMBER, 2025

CERTIFICATION

This is to certify that this project work was carried out by **ABUAH IKECHUKWU VALENTINE** with Matriculation Number **ENG2008265** of the Department of Civil Engineering. It is adequate and satisfactory, both in scope and content, for the award of bachelor of civil Engineering (B.ENG) degree of the University of Benin

ENGR. DR. IDOWU ILABOYA PROJECT SUPERVISOR	**DATE**
ENGR. PROF. (MRS) N IHIMEKPEN HEAD OF DEPARTMENT	**DATE**

DEDICATION

This project is dedicated to God Almighty for granting me the strength, wisdom, and guidance to successfully complete it and for His support throughout my time at the University of Benin (UNIBEN). I also dedicate this work to my parents, **Mr. and Mrs. TOM ABUAH,** as well as my siblings, **Mr. Vincent Abuah and Miss Chioma Abuah,** and **My Extended Family** for their unwavering love, encouragement, and support throughout my academic journey.

ACKNOWLEDGEMENT

I am deeply grateful to God Almighty for providing me with strength, wisdom, and direction throughout my academic journey. I also extend my sincere appreciation to my project supervisor, Engr. Dr. Idowu Ilaboya , whose steadfast support and guidance were instrumental in the successful completion of this project.

I would also like to extend my special thanks our Head of the Department, Engr. Prof. (Mrs) N Ihimekpen and to my project coordinator, Engr. Prof. O.U. Orie. To the esteemed lecturers of the Department of Civil Engineering, whose knowledge and guidance have profoundly impacted me over the years. I am especially grateful to Engr. Prof. (Mrs.) N. I. Ihimekpen (Ag. HOD), Engr. Prof. O.C. Izinyon, Engr. Prof. O.U. Orie, Engr. Prof. S.O. Osuji, Engr. Prof. H.A.P. Audu, Engr. Prof. J.O. Okovido, Engr. Prof. S.D. Iyeke, Engr. Prof. R.I. Umasabor, Engr. Prof. R.O. Ogirigbo, Engr. Prof. (Mrs.) N. Kayode-Ojo, Engr. Dr. (Mrs.) A. Rawlings, Engr. Dr. (Mrs.) L.O. Bobor, Engr. Dr. A. Agbonaye, Engr. Dr. S. Okonofua, Engr. Dr. R. Ilaboya, Engr. Dr. U. Ukeme, Engr. Dr. I. Inerhunwa, Engr. Dr. P.N. Ogbeifun, Engr. E. Oria-Usifo, Engr. Dr. S.A. Adegbemileke, Engr. O. Oriakhi, Engr. B. Omosefe, Engr. C.M. Okolie, Engr. O. Osasu, Engr. N.K. Oghoyafedo, Engr. (Mrs.) E. Ambrose-Agabi, Engr. A.E. Musa, Engr. (Mrs.) G.E. Evbaru-Okhuahesuyi, and Engr. J.O. Odemerho for their valuable contributions to my academic growth.

Finally, I deeply appreciate everyone who contributed to the success of this project, and I extend my gratitude to my family and friends for their unwavering support, encouragement, and guidance throughout this journey.

ABSTRACT

This study assesses the efficiency of activated carbon in treating copper nitrate-contaminated borehole water for domestic and irrigation purposes. The increasing contamination of groundwater by heavy metals and nitrates poses serious environmental and public health concerns, particularly in developing regions. The aim of this research was to evaluate the ability of activated carbon to reduce copper and nitrate concentrations in borehole water and to determine its suitability for sustainable water reuse.

Borehole water samples contaminated with copper ions (Cu^{2+}) and nitrate were treated with activated carbon at different contact times under laboratory conditions. Physicochemical parameters such as pH, electrical conductivity, turbidity, copper concentration, and nitrate concentration were analyzed before and after treatment using standard laboratory methods. Adsorption behavior was evaluated using Langmuir and Freundlich isotherm models, while adsorption kinetics were investigated using pseudo-first-order and pseudo-second-order kinetic models to understand the mechanism of adsorption.

The results showed a significant reduction in copper and nitrate concentrations after treatment with activated carbon. The Langmuir isotherm model showed the best fit with correlation coefficients (R^2) of 0.9949 for copper and 0.9861 for nitrate, indicating monolayer adsorption on a homogeneous surface. The Freundlich model also showed good correlations ($R^2 = 0.9500$ for copper and 0.9624 for nitrate). Kinetic analysis revealed that the pseudo-second-order model better described the adsorption process, with R^2 values of 0.9824 for copper and 0.8049 for nitrate. The treated water quality improved and was suitable for irrigation and moderately improved for domestic use, confirming that activated carbon is an effective and low-cost adsorbent for reducing copper nitrate contamination in borehole water.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

Water is a vital resource required for human survival, agricultural production, and economic development. In many developing countries, including Nigeria, groundwater obtained through boreholes serves as the main source of water for domestic and irrigation purposes due to its availability and perceived cleanliness (Aluko et al., 2023). However, rapid population growth, industrial expansion, agricultural intensification, and poor waste management practices have contributed to the gradual deterioration of groundwater quality in recent years (Asomaku, 2023). One major threat to groundwater quality is the presence of heavy metals. These contaminants may originate from natural geological formations as well as human activities such as industrial discharge, corrosion of water pipes, mining operations, and the application of agrochemicals (Ugwu et al., 2024). Copper (Cu^{2+}) is among the commonly detected heavy metals in groundwater systems.

Copper is an essential micronutrient for both humans and plants, excessive exposure can lead to serious health and environmental problems (Liu, 2023). High concentrations of copper in drinking water have been associated with gastrointestinal disorders, liver damage, and kidney dysfunction when consumed over long periods (WHO, 2022). In agriculture, excessive copper in irrigation water can lead to soil contamination, reduced nutrient availability, and poor crop performance (Ayers and Westcot, 2020). According to the World Health Organization, the maximum permissible limit of copper in drinking water is 2.0 mg/L (WHO, 2022). Similarly, the Standards Organisation of Nigeria prescribes the same limit in the Nigerian Standard for Drinking Water Quality (SON, 2021).

Recent studies conducted in different regions of Nigeria have reported elevated concentrations of copper and other heavy metals in borehole water, particularly in urban and industrialized areas (Nofiu and Gbadebo, 2024; Aluko et al., 2023). These findings indicate that groundwater contamination is becoming a serious environmental and public health concern.

Among the various treatment methods available for heavy metal removal, adsorption has been widely recognized as an efficient and cost-effective technique (Neisan et al., 2023). Activated carbon is one of the most effective adsorbents due to its high surface area, porous structure, and strong affinity for metal ions (Pet, 2024). In Nigeria, agricultural wastes such as rice husks, coconut shells, and palm kernel shells can be converted into activated carbon, making the technology environmentally sustainable and economically viable.

This study therefore evaluates the efficiency of activated carbon in removing copper nitrate from borehole water. The outcome is expected to contribute to improving water quality and supporting sustainable domestic and agricultural water use.

1.2 Statement of the Problem

Borehole water is widely relied upon by Nigerian communities because it is considered safer than surface water. However, recent investigations show that groundwater quality is declining due to increasing contamination from human and natural sources (Asomaku, 2023). Industrial effluents, agricultural runoff, waste dumps, and mineral leaching processes introduce heavy metals into underground water systems.

Copper contamination in borehole water has become a growing concern. When present above recommended limits, copper poses risks to human health and agricultural productivity. Prolonged consumption of copper-rich water may cause digestive disorders and organ damage, while continuous irrigation with contaminated water may lead to soil degradation and reduced crop yield (Liu, 2023; Ugwu et al., 2024).

Despite these risks, many communities lack access to advanced water treatment facilities. Conventional treatment methods such as membrane filtration and ion exchange are effective but are often expensive, technically demanding, and difficult to maintain (Neisan et al., 2023). As a result, untreated or poorly treated water is commonly used.

Activated carbon produced from locally available materials offers a promising alternative because of its affordability and high adsorption capacity. However, limited studies have evaluated its performance under local groundwater conditions where competing ions and varying water chemistry may affect removal efficiency. This study therefore seeks to bridge this gap by assessing the effectiveness of activated carbon in treating copper nitrate-contaminated borehole water.

1.3 Aim of the Study

The aim of this study is to evaluate the effectiveness of activated carbon in the removal of copper nitrate from borehole water to ensure its suitability for domestic and irrigation purposes.

1.4 Objectives of the Study

The specific objectives are to:

i. Determine the initial concentration of copper and nitrate ions in borehole water samples from selected sites.
ii. Treat the borehole water using activated carbon at controlled contact conditions.
iii. Evaluate the efficiency of copper and nitrate removal by activated carbon.
iv. Examine the improvement in selected physicochemical water quality parameters such as pH, electrical conductivity (EC), turbidity, and total dissolved solids (TDS) following treatment.

v. Compare the quality of treated water with WHO and SON standards for drinking and irrigation water.

1.4 Scope of the Study

This study is limited to the assessment of copper and nitrate contamination in borehole water and the evaluation of activated carbon as a treatment method for their removal. Borehole water samples were collected from selected locations within the study area to represent typical groundwater conditions experienced by local users. The investigation focused specifically on copper ions (Cu^{2+}) and nitrate due to their increasing occurrence in groundwater and their potential health and agricultural impacts.

The treatment method employed in this study was restricted to adsorption using activated carbon under controlled laboratory conditions. The activated carbon was prepared and applied at varying dosages and contact times to determine its effectiveness in removing copper and nitrate from contaminated water. Other physicochemical parameters such as pH, turbidity, electrical conductivity, and total dissolved solids were not analyzed in this study, as the primary emphasis was placed on evaluating metal and nitrate removal efficiency.

Assessment of water suitability was carried out by comparing the post-treatment concentrations of copper and nitrate with established drinking and irrigation water standards provided by the World Health Organization and the Food and Agriculture Organization of the United Nations (WHO, 2017; FAO, 2005). This comparison was used to determine whether the treated water met acceptable limits for domestic and agricultural use.

The study did not include biological analysis, microbial contamination assessment, or the investigation of organic pollutants and other heavy metals. Advanced treatment techniques such as membrane filtration, ion exchange, and chemical oxidation were also beyond the scope of this research. Furthermore, long-term field performance, large-scale system design, and operational optimization were not considered. The investigation was therefore confined to laboratory-based evaluation of activated carbon for copper and nitrate removal from borehole water.

1.5 Significance of the Study

This study is significant due to its relevance to public health, environmental protection, and socio-economic development in communities that rely heavily on borehole water for daily activities. Consumption of water contaminated with heavy metals such as copper poses serious health risks, including gastrointestinal disorders and long-term organ damage. By investigating an effective method for reducing copper and nitrate concentrations to acceptable levels, this research contributes to the promotion of safe drinking water and the prevention of water-related diseases (WHO, 2017).

In the agricultural sector, water quality plays a vital role in sustaining crop productivity and soil fertility. The continuous use of irrigation water containing excessive copper can lead to soil contamination, nutrient imbalance, and reduced plant growth, which may negatively affect food production and farmers' livelihoods. The findings of this study therefore support sustainable agricultural practices by ensuring that irrigation water does not compromise soil health or crop yield (FAO, 2005).

From an environmental perspective, this research promotes sustainable resource management through the use of activated carbon derived from agricultural waste materials. The conversion of biomass residues into useful adsorbents reduces environmental pollution, encourages waste recycling, and supports eco-friendly water treatment practices. Such approaches are consistent with global efforts toward environmental sustainability and climate-resilient development (World Bank, 2019).

Economically, the study provides a low-cost and practical water treatment option that can be adopted by low-income households and rural communities where access to advanced treatment technologies is limited. The use of locally sourced materials for activated carbon production enhances affordability and accessibility, thereby promoting equitable access to safe water and supporting community development.

Academically and institutionally, this study contributes valuable experimental data on the efficiency of activated carbon in removing copper and nitrate from groundwater. The results can serve as a reference for researchers, environmental professionals, and policymakers involved in water resource management. The findings may guide future research, influence policy formulation, and strengthen decision-making processes aimed at improving water quality and safeguarding public health.

Overall, this study contributes to the advancement of public health protection, agricultural sustainability, environmental conservation, economic empowerment, and scientific knowledge. Its outcomes are expected to support practical improvements in groundwater treatment while enhancing understanding of sustainable and affordable water purification methods.

CHAPTER TWO

LITERATURE REVIEW

2.1. Water

Water quality assessment has become increasingly important as many communities depend on groundwater for their daily water supply and agricultural irrigation needs. However, contamination by heavy metals, especially copper ions originating from corrosion of pipes, industrial discharges, agrochemicals, and waste infiltration, has raised significant health and environmental concerns. Excess copper in borehole water causes metallic taste, pipeline staining, and long-term health issues such as gastrointestinal discomfort and liver disorders when used for domestic purposes. In irrigation, high copper concentration inhibits root development, disrupts nutrient absorption, and leads to reduced crop productivity and soil fertility decline over time.

To ensure that borehole water is safe and fit for both domestic and irrigation uses, there is a strong need for effective purification systems capable of reducing copper ion levels to recommended guideline values. Activated carbon has increasingly gained recognition as a cost-effective treatment method due to its large surface area, porous structure, and ability to adsorb dissolved metal ions. The approach is especially suitable for rural regions where household boreholes serve as the primary water source and access to advanced water-treatment facilities is limited.

Therefore, the removal of copper ions from borehole water using activated carbon is essential for safeguarding public health and sustaining agricultural productivity. This study focuses on determining how effectively activated carbon can adsorb copper ions and improve water quality to meet both drinking water standards and irrigation suitability guidelines. The outcome will support communities relying on boreholes by providing evidence-based solutions for reducing copper contamination using an affordable and locally adaptable treatment technique.

2.2 Taste and Aesthetic Quality of Copper-Contaminated Borehole Water

Even when borehole water appears safe from a microbiological standpoint, the presence of dissolved copper ions can significantly alter its aesthetic qualities. Elevated concentrations of copper impart a metallic taste and may cause blue-green staining of plumbing fixtures and water storage containers. These noticeable changes often reduce consumer confidence and discourage use for drinking and food preparation, even when the water may still fall within borderline chemical standards.

Recent findings by Afolabi and Okeke (2021) revealed that borehole water with copper levels above 1.5 mg/L exhibited strong metallic aftertaste, prompting household rejection despite being the only available source. In cases of prolonged exposure, copper concentrations exceeding guideline values may cause nausea and gastric irritation, further contributing to public concern (Torres and Almeida, 2020).

Although the taste of irrigation water is not directly important, aesthetic issues remain relevant in areas with irrigation systems located near residential communities or food processing sites. Blue-green discoloration in irrigation equipment can lead to negative perception of agricultural products and concerns over safety and market value.

Activated carbon has proven effective in improving water aesthetics in addition to its copper removal function. Due to its high surface area and porous structure, activated carbon adsorbs dissolved copper ions responsible for metallic taste, restoring water to a more pleasant and perceptible quality (Nwosu and Ani, 2022). This dual functionality chemical purification and sensory improvement strengthens the role of activated carbon in enhancing both user acceptance and safe water utilization.

2.2.1 Understanding Borehole Water Contamination and the Need for Purification

Borehole water is widely considered a dependable source of freshwater for drinking and agricultural activities, especially in regions lacking municipal supply systems. However, increasing human activities have led to deterioration in groundwater quality, particularly through the intrusion of heavy metals such as copper. Studies between 2020 and 2024 (Adepoju and Balogun, 2020; Mensah et al., 2023) show that corrosion of plumbing networks, leachate from waste disposal sites, industrial discharges, and copper-based agrochemicals contribute significantly to copper contamination in groundwater aquifers.

Excess copper ions in borehole water pose dual risks. For domestic users, concentrations beyond recommended limits cause gastrointestinal irritation, metallic taste, and potential liver complications (Torres and Almeida, 2020). For crop production, Cu^{2+} accumulation induces root toxicity, chlorosis, and yield reduction due to interference with essential nutrient uptake (Ojo and Ibrahim, 2021). Because copper nitrate remains highly soluble, natural filtration processes fail to adequately remove it, allowing contamination to persist and spread through aquifers (Bello et al., 2023).

To maintain safe usability, effective purification systems are necessary. Activated carbon has been recognized as a practical and affordable adsorbent, particularly where financial constraints limit access to sophisticated water-treatment technologies (Ndlovu and Mpofu, 2022). Its high porosity and surface chemistry enable strong copper ion capture through adsorption and complexation mechanisms, improving water quality to levels suitable for both drinking and irrigation purposes.

Therefore, copper removal using activated carbon provides not only chemical safety but also boosts confidence and encourages continued reliance on groundwater resources for household and agricultural needs, especially in low-income communities.

2.2.2 Copper Nitrate in Groundwater: Sources and Behavior

Copper nitrate is a highly soluble salt formed when copper ions react with nitrate-bearing compounds in the environment. It readily dissolves into groundwater due to leaching from geological deposits, corrosion of copper-based plumbing, industrial discharge, mining residues, and agricultural waste runoff (Adeleke et al., 2023). Fertilizers containing nitrate can also increase the mobility of copper, enhancing its dissolution and transport into boreholes (Babel and Kurniawan, 2020).

Once introduced into groundwater, copper nitrate dissociates into free Cu^{2+} ions and nitrate (NO_3^-) ions. The behavior of copper in water is strongly dependent on pH, redox environment, and dissolved organic matter. Under acidic conditions, mobility and bioavailability increase due to reduced adsorption onto aquifer minerals (Gao et al., 2022). Because nitrate is also highly mobile and resistant to natural attenuation, copper nitrate contamination can persist for long periods.

Regulatory bodies have set permissible limits to minimize human and environmental risks. WHO (2022) recommends a copper guideline value of 2 mg/L for drinking water, while nitrate should remain below 50 mg/L. For irrigation, FAO (2021) suggests that excessive copper can impede nutrient uptake and lower crop productivity. Exceeding these limits highlights the need for effective water treatment technologies.

2.2.3 Health and Environmental Impacts of Copper Nitrate Contamination

Copper plays an essential role in metabolic processes at trace levels; however, excessive intake results in toxicity. Health risks include gastrointestinal irritation, oxidative stress, liver and kidney damage, especially among children and pregnant women (WHO, 2022). Nitrate ingestion can also induce methemoglobinemia (“blue baby syndrome”) when converted into nitrites in the body (Gao et al., 2022).

From an agricultural perspective, copper accumulation in soils suppresses root elongation, damages leaf chlorophyll pigments, and interferes with phosphorus uptake, reducing yields (FAO, 2021). Bioaccumulation poses risks to livestock and humans through crop consumption. Long-term contamination can also deteriorate soil structure and microbial activity.

Thus, treating affected borehole water before domestic or irrigation use is critical for public health and environmental sustainability.

2.3 Treatment Technologies for Copper Nitrate Removal

Several conventional and advanced methods exist for removing copper and nitrate from contaminated water, including:

Table 2.1: Comparison of Treatment Technologies for Copper and Nitrate Removal

Method	**Advantages**	**Limitations**
Chemical precipitation	Effective for high metal concentrations	High sludge production
Ion exchange	High removal efficiency	Expensive resins, skilled operation
Membrane filztration (RO/NF)	Removes diverse contaminants	High energy demands, fouling issues
Chemical reduction	Applicable for nitrate removal	Produces secondary contaminants
Electrochemical methods	Efficient and fast	Capital-intensive
Adsorption	Cost-effective, scalable	Adsorbent regeneration required

(Source: Nwabanne and Okoye, 2021)

Among these, adsorption particularly using activated carbon has emerged as a reliable and low-cost method. It combines high removal efficiency, simple design, and limited chemical use (Moyo et al., 2022). These characteristics make it suitable for rural borehole treatment applications.

2.4 Activated Carbon: Production and Properties

Activated carbon (AC) is produced from carbonaceous materials such as coconut shells, coal, wood, and agricultural residues. Production involves carbonization followed by activation either:

i. Physical activation (steam or CO_2 at 700-900°C)
ii. Chemical activation (acidic or alkaline activators such as H_3PO_4, $ZnCl_2$, KOH)

Chemical activation is widely used for biomass-derived carbons due to shorter processing time and enhanced surface development (Mohammed et al., 2023).

Key properties influencing adsorption performance include:

i. Surface area and pore volume: micropores facilitate retention of ions
ii. Surface functional groups (-OH, -COOH, -C=O): form complexes with metal ions
iii. Porosity distribution: determines accessibility to nitrate and copper ions

Studies have shown that AC produced from agricultural by-products like rice husk, palm kernel shell, and sawdust demonstrates strong ability to remove heavy metals including copper from water (Moyo et al., 2022). Utilizing agricultural waste for AC aligns with circular economy goals and reduces material costs.

2.5 Adsorption Mechanisms of Copper Nitrate onto Activated Carbon

The removal of copper nitrate by AC occurs through multiple simultaneous processes:

i. Physical adsorption: pore filling regulated by Van der Waals forces

ii. Chemisorption: strong interaction via functional groups forming inner-sphere complexes with Cu^{2+}
iii. Ion exchange: displacement of surface-bound ions by copper ions
iv. Electrostatic attraction: dependent on pH and surface charge
v. Surface precipitation: formation of copper hydroxide at high pH levels

The relative contribution of these mechanisms depends on AC properties and water chemistry. pH is the most influential parameter; low pH favors mobile Cu^{2+}, while moderate pH enhances adsorption through deprotonation of surface functional groups (Gao et al., 2022). Modifications such as acid treatment or impregnation with metal oxides can enhance density of active sites, thereby increasing selectivity and adsorption capacity (Mohammed et al., 2023).

2.6 Chemistry and Behavior of Copper Nitrate in Borehole Water

Copper nitrate, $Cu(NO_3)_2$, is a highly soluble compound that releases Cu^{2+} ions and NO_3^- ions once dissolved in groundwater. Recent studies (Afolabi and Okeke, 2021; Bello et al., 2023) showed that nitrate ions form aqueous complexes that stabilize copper species, preventing natural precipitation or adsorption onto aquifer minerals. As a result, copper nitrate migrates freely through permeable soils, especially under acidic conditions common in areas with agricultural runoff. Elevated copper causes metallic taste and staining in drinking water, while prolonged exposure results in gastrointestinal and liver damage (Torres and Almeida, 2020). In agricultural use, concentrations beyond threshold values lead to phytotoxicity, root inhibition, crop yield reduction, and long-term soil accumulation (Ojo and Ibrahim, 2021). Therefore, removal of copper nitrate from borehole sources remains critical in safeguarding human and environmental health, particularly in rural communities dependent on groundwater.

2.7 Borehole Water Contamination with Heavy Metals

Although borehole water is often considered safer due to natural filtration, anthropogenic activities continue to compromise groundwater integrity. Between 2019 and 2024, several investigations across sub-Saharan Africa (Adepoju and Balogun, 2020; Onuoha et al., 2024) identified copper contamination arising from corroded plumbing, pesticide-laden runoff, mining sites, waste dumpsites, and industrial effluents. Copper nitrate specifically persists because its ions do not readily adsorb onto clay surfaces, allowing deep aquifer penetration (Mensah et al., 2023). Once groundwater becomes contaminated, remediation becomes complex due to poor well construction and limited community monitoring structures. With waterborne heavy-metal toxicity rising globally, reliance on untreated borehole water poses significant risks for populations lacking municipal supply.

2.8 Water Quality Standards for Domestic and Irrigation Use

International bodies enforce strict standards to minimize health risks. The WHO (2022) recommends copper levels ≤ 2.0 mg/L in drinking water, while the Standard Organization of Nigeria sets similar upper limits. Research by Abbas and Nsaif (2019) revealed that chronic exposure above permissible levels increases the likelihood of liver and neurological disorders. For irrigation, the FAO (2023) highlights that long-term copper accumulation disrupts nutrient uptake, induces oxidative stress in crops, and alters beneficial soil microbial communities, negatively affecting yield. Hence, ensuring copper-nitrate-polluted borehole water meets both drinking and agricultural safety criteria remains a key requirement for sustainable resource management.

2.8.1 Overview of Treatment Methods for Copper-Polluted Water

Several heavy-metal removal processes exist, including precipitation, electrodeposition, ion exchange, advanced oxidation, and membrane filtration. However, most technologies in published studies from 2019-2024 (Chigozie et al., 2023; Zairi et al., 2023) show limitations such as high operational cost, skilled personnel demands, and residual waste generation. Adsorption using activated carbon (AC) stands out because it offers cost-effectiveness, energy efficiency, and operational simplicity   factors suitable for rural water treatment facilities. In particular, AC demonstrates strong affinity for copper species due to its tunable surface chemistry and porous structure (Ndlovu and Mpofu, 2022).

2.8.2 Adsorption Principles and Activated Carbon

Activated carbon is predominantly sourced from agricultural waste materials like rice husk, coconut shells, sawdust, and palm kernel shells   making it environmentally beneficial and locally accessible (Oladoja et al., 2021). During activation, a network of micro- and mesopores forms, accompanied by oxygen-containing surface groups (hydroxyl, carboxyl, carbonyl). These enhance adsorption through ion exchange, electrostatic attraction, and surface complexation. Recent findings (Osei and Boateng, 2024) confirm that properly structured AC captures dissolved Cu^{2+} even in the presence of nitrate complexes, making it promising for borehole water purification.

2.9 Adsorption Kinetics and Equilibrium Models

Adsorption behavior is typically evaluated through kinetic and isotherm models, which provide insights into mechanisms, reaction rates, and surface interactions occurring between adsorbents and metal ions. In the context of copper removal using activated carbon, these models help determine whether uptake is controlled by diffusion, physical attraction, or chemical bonding. They also clarify whether adsorption occurs on uniform or diverse surface sites, influencing both design and optimization of treatment processes.

2.9.1 Pseudo-First-Order Kinetic Model

The pseudo-first-order model describes adsorption processes where the rate of solute uptake is proportional to the number of available sites. It is commonly associated with physical adsorption (physisorption) involving weak van der Waals forces. Initial adsorption tends to be rapid due to the abundance of unoccupied active sites, followed by a slower phase as equilibrium approaches. However, several studies on copper ions have reported that this model often underestimates equilibrium capacity, indicating it may not fully capture the interaction strength between copper ions and activated carbon surfaces (Torres and Almeida, 2020). Thus, while useful for preliminary assessment of rate behavior, its applicability to transition metal ion adsorption is somewhat limited

2.9.2 Pseudo-Second-Order Kinetic Model

The pseudo-second-order model is widely recognized as the most suitable representation of heavy metal adsorption onto activated carbons. It assumes that the rate-limiting step involves chemisorption, characterized by electron sharing or exchange between functional groups on the adsorbent and metal ions. Recent studies from 2021-2024 have consistently reported high correlation coefficients (R^2 values) when applying this model to copper removal from aquatic systems (Nwosu and Ani, 2022). Its robustness demonstrates the strong interaction energy required for Cu^{2+} fixation, indicating better prediction of equilibrium behavior than the pseudo-first-order model.

2.9.3 Langmuir Isotherm Model

The Langmuir isotherm describes adsorption onto homogeneous surfaces where all adsorption sites are identical and energetically equivalent. It assumes monolayer coverage, meaning each active site can hold only one adsorbate molecule, with no interaction between neighboring adsorbed ions. This model provides an important parameter known as maximum adsorption capacity (q_max), essential for engineering applications. Numerous copper adsorption experiments using both commercial and bio-derived activated carbon have been demonstrated to closely follow Langmuir behavior (Bello et al., 2023), reinforcing the presence of uniform metal-binding sites and strong affinity.

2.9.4 Freundlich Isotherm Model

The Freundlich isotherm is an empirical model used to describe adsorption on heterogeneous surfaces with varying energy strengths. Unlike the Langmuir model, it permits multilayer adsorption, making it particularly suitable for natural water systems where competing ions and organic matter alter surface chemistry. The Freundlich constant (1/n) further indicates surface intensity and favorability of adsorption; values between 0 and 1 typically signify effective removal. Studies involving borehole water and real wastewater samples have shown improved fitting to this model, suggesting diverse activated carbon active sites and complexity of copper adsorption in non-ideal environments (Mensah et al., 2023).

2.10 Operational Factors Influencing Copper Nitrate Removal

2.10.1 pH

Adsorption improves around neutral pH, which aligns with natural borehole conditions (FAO, 2023).

2.10.2 Adsorbent Dosage

Increasing AC mass raises metal uptake until equilibrium saturation is achieved (Chukwu and Ezenwa, 2022).

2.10.3 Contact Time

Copper ions show rapid initial capture followed by gradual progression toward stability (Abbas and Nsaif, 2019).

2.10.4 Regeneration and Reusability of Activated Carbon

Sustainable adsorption depends on restoration of carbon after saturation. Recent studies from 2020-2024 suggest thermal, chemical, or electrochemical regeneration methods (Osei and Boateng, 2024). However, repeated cycles may degrade pores or introduce chemical residue. Striking the balance between regeneration cost and performance is essential for rural water-treatment adoption.

2.11 Activated Carbon as a Tertiary Treatment Option

Activated carbon is a form of carbon that has been specially processed to have a large number of tiny pores, giving it a very high surface area. This makes it excellent at trapping and holding pollutants from water or air. It is commonly made from materials like wood, coal, or coconut shells. In water treatment, it helps remove chemicals, bad smells, and harmful substances. Activated carbon is often used as a final step to clean water before it's reused or released. Its strong filtering ability makes it a key tool in producing safe and clean water.

2.11.2 Activated carbon as an adsorbent for water treatment

Activated carbon is widely recognized as one of the most effective adsorbents used in water and wastewater treatment due to its highly porous structure, large surface area, and strong adsorptive capacity. It is typically produced from carbon-rich organic materials such as coal, coconut shells, wood, and agricultural waste through thermal or chemical activation processes that significantly enhance its porosity and surface reactivity. The resulting material exhibits a vast network of micro-, meso-, and macropores, which facilitate the physical and chemical adsorption of a wide variety of contaminants.

In the context of treated effluent reuse, activated carbon plays a critical role in polishing water removing residual contaminants that escape conventional treatment. Its adsorption mechanisms are primarily based on Van der Waals forces, electrostatic interactions, and pore filling, allowing it to trap a broad range of substances including organic micro pollutants, chlorine by-products, pesticides, endocrine-disrupting compounds, pharmaceuticals, taste- and odour-causing compounds, and even some heavy metals. These capabilities make it highly valuable in improving the aesthetic and chemical quality of effluent intended for domestic and irrigation purposes.

Activated carbon can be applied in powdered (PAC) or granular (GAC) form. PAC is often added directly to the water and removed later by sedimentation or filtration, while GAC is typically used in fixed-bed filters through which water flows. The selection between PAC and GAC depends on the operational scale, targeted contaminants, and specific reuse objectives. For instance, GAC is more suitable for continuous systems with long contact times, such as tertiary treatment stages in wastewater plants aimed at producing high-quality reuse water.

The performance of activated carbon is influenced by several factors, including pH, temperature, contact time, surface chemistry, and the nature and concentration of the pollutants. Studies published between 2020 and 2024 have explored the modification of activated carbon to improve its selectivity and adsorption efficiency. Surface oxidation, metal impregnation, and functionalization with polymers or nanoparticles are some of the techniques that have been employed to enhance its effectiveness for specific contaminants.

Moreover, activated carbon derived from low-cost materials such as agricultural by-products (e.g., rice husks, date pits, and sugarcane bagasse) has been extensively studied and shown to offer comparable performance to commercial carbon, making it a sustainable and economical option for developing regions or rural wastewater treatment applications. These modified or bio-based carbons also support circular economy principles by utilizing waste to treat waste.

2.11.3 Effectiveness of Activated Carbon in Improving Copper-Contaminated Borehole Water

Activated carbon has proven to be highly efficient in treating borehole water contaminated with copper ions due to its exceptional adsorption capacity. Unlike basic treatment methods that primarily remove suspended solids or pathogens, activated carbon effectively targets dissolved pollutants. Its large surface area and highly porous microstructure allow Cu^{2+} ions to attach strongly onto adsorption sites through ion exchange, electrostatic attraction, and surface complexation.

Research published between 2020 and 2024 demonstrates that activated carbon derived from agricultural wastes such as coconut shells, rice husk, and palm kernel shells can significantly reduce copper concentrations in groundwater. Besides removing copper, activated carbon also improves aesthetic quality by reducing turbidity, unwanted coloration, and metallic taste often associated with elevated copper levels. This makes the water more suitable for household uses like drinking, cooking, and cleaning.

In agricultural application, lowering heavy metal content prevents phytotoxicity, ensuring crops can absorb nutrients without interference. Thus, activated carbon plays a dual role: meeting health-based drinking standards while enhancing the usability of borehole water for irrigation under local and international guidelines.

2.11.4 Comparison of Activated-Carbon-Treated Borehole Water With Standards

When borehole water contaminated with copper ions is treated using activated carbon, final water quality often aligns with and sometimes exceeds regulatory benchmarks. Global standards such as those from the World Health Organization (WHO) and the Nigerian

Standard for Drinking Water Quality (NSDWQ) recommend copper concentrations not exceeding 2.0 mg/L for safe domestic consumption. Most recent adsorption studies (2021-2024) record copper removal efficiencies above 80-95%, successfully reducing initial concentrations below permissible levels.

For irrigation purposes, guidelines issued by the Food and Agriculture Organization (FAO) stress limiting excessive metals to protect soil structure, plant growth, and microbial activity. Activated-carbon-treated groundwater typically falls within safe thresholds for crop irrigation, improving agricultural sustainability.

Additionally, enhancements in taste, odor, clarity, and color quality support community acceptance an important factor in rural water supply systems. After AC treatment, parameters such as pH, turbidity, and conductivity also approach recommended ranges for multipurpose water use.

2.12 Water Quality and Suitability Standards

2.12.1 Key Parameters for Assessing Copper-Contaminated Borehole Water

Table 2.2: Key Parameters and Their Significance for Copper-Contaminated Borehole Water

Parameter	**Significance**
Copper (Cu^{2+})	Must remain ≤ 2.0 mg/L for drinking; excessive levels toxic to humans and crops
pH	Should remain neutral (6.5-8.5) to avoid increased metal solubility
Turbidity	Low values improve aesthetics and prevent pathogen survival

Total Dissolved Solids (TDS) Electrical Conductivity (EC)	Excess salinity affects soil permeability and plant health
Microbial indicators (e.g., coliform count)	Essential for safe domestic use, especially drinking
Other heavy metals (Fe, Pb, Cd, etc.)	Ensure no secondary contamination from natural geology or plumbing

Source: Adapted from WHO (2017); FAO (2005)

These indicators collectively determine whether borehole water is fit for drinking and agricultural applications.

2.12.2 Standards for Domestic and Irrigation Water Use

WHO (2022) **sets limits for metals, microbial safety, pH, and turbidity to ensure water is healthy for consumption.**

i. FAO (2023) provides irrigation guidelines to prevent soil degradation and crop metal accumulation.
ii. NSDWQ (2015) establishes national thresholds for copper, pH, and other important parameters for Nigerian consumers.

Adherence to these standards confirms whether treated water is safe and sustainable for its intended uses.

2.13 Role of Activated Carbon in Sensory Improvement

Activated carbon effectively removes sensory pollutants through surface adsorption of:

i. metallic-taste ions (Cu^{2+})
ii. volatile organic compounds (VOCs)
iii. foul-smelling gases (e.g., H_2S)

By improving color, flavor, and smell, AC greatly enhances public confidence in treated borehole water and supports widespread adoption for domestic and irrigation purposes.

2.13.1 Advantages of using activated carbon

i. Cost-effective: especially when produced locally.

ii. Simple operation: suitable for rural and semi-urban setups.

iii. High adsorption capacity: removes both organic and inorganic pollutants.

iv. Improves sensory qualities: eliminates bad taste and odor.

v. S.calable: can be used in batch or continuous systems.

2.13.2 Limitations of activated carbon use

i. Saturation: needs periodic replacement or regeneration.

ii. Cost of commercial AC: can be high if imported.

iii. Disposal issues: spent carbon may retain harmful pollutants.

iv. Selective adsorption: not all pollutants are removed equally.

2.14 Taste and Odor Characteristics of Copper Nitrate in Borehole Water

Although copper nitrate contamination is primarily evaluated based on toxicity and regulatory limits, its presence also affects the sensory quality of water. When dissolved, copper nitrate releases Cu^{2+} ions that impart a noticeable metallic taste and may contribute to discoloration or a faint chemical odor. These aesthetic changes influence public acceptability, especially for domestic consumption or food preparation purposes (Ojo and Ibrahim, 2021). Even when copper concentrations are within safe limits, taste-based rejection often leads consumers to avoid using borehole water, preferring alternative sources when possible.

2.14.1 Importance of Taste and Odor in Water for Domestic and Irrigation Use

While taste and odor do not always determine the health safety of copper-polluted water, they serve as crucial indicators of pollution and treatment quality. In households, strong metallic taste or unpleasant smell discourages direct use, undermining community confidence in borehole water supplies (Ayoade, 2021). For irrigation, objectionable odors can raise concerns about the sanitary state of water, affecting farmworker acceptance and market appeal of crops irrigated with such water. Therefore, improving sensory properties is essential for maintaining both functional and user satisfaction standards.

2.14.2 Sensory Effects Linked to Copper Nitrate Contamination

Table 2.3: Common Sensory Effects Associated with Copper Nitrate in Groundwater

Sensory Effect	**Cause**
Metallic or bitter taste	High concentrations of Cu^{2+} ions
Slight chemical odor	Interaction between nitrate ions and natural organic matter
Blue-green staining of fixtures	Copper dissolution and precipitation reactions
Water discoloration over storage	Oxidation of copper ions producing visible compounds

Source: Adapted from Nwabanne and Okoye (2021); WHO (2017)

These properties degrade aesthetic quality, even at moderately elevated levels.

2.14.3 Role of Activated Carbon in Improving Taste and Odor Quality

Activated carbon is highly effective in restoring the sensory quality of borehole water impacted by copper nitrate. Its microporous surface adsorbs dissolved metal ions and trace organics responsible for undesirable flavor and odor, resulting in cleaner and more palatable water. Studies by Ndlovu and Mpofu (2022) show that activated carbon can significantly reduce metallic taste intensity by removing over 80% of aqueous Cu^{2+} ions under optimized conditions.

Powdered activated carbon (PAC) offers high reactivity due to its greater surface area contact, while granular activated carbon (GAC) provides continuous filtration benefits in fixed-bed systems. Removal efficiency is influenced by:

i. contact time between water and carbon
ii. carbon dosage
iii. pore size distribution

By improving taste and odor while also lowering copper to regulatory limits, activated carbon enhances both health safety and public acceptance of treated borehole water for domestic and irrigation uses.

2.15 Case Studies and Research Evidence from Edo State, Nigeria

2.15.1 Copper-Related Water Quality Challenges in Benin City

Recent water quality assessments conducted within Benin City and surrounding communities have reported elevated levels of heavy metals particularly copper, iron, and manganese in groundwater sources such as boreholes. These contaminants are linked to industrial activities, corroded pipelines, and leaching from waste disposal sites (Oghenevwiro and Uhunmwangho, 2022; Okoro et al., 2023).

Studies conducted within the University of Benin (UNIBEN) campus between 2021 and 2023 identified copper concentrations in borehole water exceeding safe thresholds recommended for drinking and irrigation (WHO, 2022; Nwankwo et al., 2023). Though the water is commonly used for domestic purposes, complaints regarding bitter metallic taste and discoloration of sinks and laundry were frequently documented. Such findings highlight the need for low-cost, locally sourced treatment alternatives that can effectively improve water quality.

Activated carbon, especially from agricultural waste, has been recommended to address these concerns due to its low cost and strong adsorption capacity toward transition metals like copper (Eze et al., 2024).

2.16 Laboratory Procedures for Activated Carbon Treatment and Analysis

2.16.1 Preparation of activated carbon

Activated carbon used in this study will be prepared from agricultural waste such as coconut shells, palm kernel shells, and sawdust.

Procedure:

i. Carbonization: raw material will be burned in limited oxygen at 400-600°C.

ii. Activation: the char will then be treated with either steam or phosphoric acid and reheated to enhance porosity.

iii. Sieving: the activated product is sieved to uniform sizes (typically less than 2 mm) for batch and column experiments.

2.16.2 Treatment of Borehole Water Samples

In this research, batch adsorption tests were carried out to evaluate the effectiveness of activated carbon in removing copper ions from borehole water obtained within the University of Benin (UNIBEN) premises. Column adsorption was not conducted in this study; however, the batch procedure followed recognized adsorption testing standards.

Batch Adsorption Tests

i. A known volume of copper-contaminated borehole water (e.g., 1000mL) was measured into a clean conical flask.

ii. A predetermined mass of activated carbon (1-5 g) was added to the sample.

iii. The mixture was agitated on a rotary shaker at 120 rpm for a contact period ranging from 10-60 minutes to facilitate adsorption.

iv. After agitation, the sample was filtered using Whatman filter paper to separate the activated carbon.

v. The filtrate was analyzed using Atomic Absorption Spectrophotometry (AAS) to determine the final copper concentration (Cf) and compute removal efficiency.

2.17 Review of Previous Relevant Literatures

Activated carbon has been widely studied for its ability to remove toxic heavy metals such as copper from contaminated water. For instance, Amin et al. (2022) achieved 92% copper ion removal from synthetic borehole water using coconut-shell activated carbon at 60 minutes contact time. Their work demonstrated the potential of low-cost carbon for metal remediation; however, the authors did not evaluate irrigation suitability post-treatment.

According to Babatunde et al. (2023), palm kernel shell-based activated carbon successfully removed 85% of Cu^{2+} from groundwater using a batch system under optimized pH conditions. The results highlight feasibility for local water purification, though the researchers did not examine long-term carbon performance or regeneration.

In a recent study by Nartey et al. (2021), powdered activated carbon (PAC) removed up to 90% of copper ions from industrial effluent. Their work also reported improvements in turbidity and conductivity, making the water more acceptable for domestic use. However, potential impacts on soil chemistry when reused for irrigation were not included.

Musa et al. (2024) evaluated granular activated carbon (GAC) in column filtration for Cu^{2+} removal from well water and recorded 88% removal efficiency. The study proved column systems effective for continuous treatment but did not assess adsorption behavior in the presence of competing ions common in borehole water.

Activated carbon’s ability to remove multiple heavy metals including copper has been documented broadly. For example, Gao et al. (2020) reported that both GAC and PAC effectively adsorb Cu^{2+} alongside Pb^{2+} and Cd^{2+} through surface complexation mechanisms. Practical application challenges such as cost and field deployment were not addressed.

As demonstrated by Oluwole et al. (2021), GAC reduced copper ion concentration in contaminated hand-pump water by 89%, also improving odor and taste properties. Despite promising results, the adsorbent's lifespan and replacement strategy were not studied.

Agricultural waste-based adsorbents have gained attention due to sustainability advantages. Sharma et al. (2020) showed that rice-husk activated carbon removed 82% Cu^{2+} under optimized pH and contact time. However, the study used synthetic lab solutions instead of real borehole water.

In a similar approach, Ibrahim et al. (2021) tested bamboo-derived activated carbon and found 90% copper removal in batch experiments. Electrical conductivity and hardness also improved, suggesting irrigation reuse potential, though microbial risks were not assessed.

Ali et al. (2022) demonstrated that palm-waste activated carbon removed 91% copper ions in fixed-bed columns while maintaining stable flow. Yet, clogging issues and backwashing requirements were not discussed, indicating scalability concerns.

In research by Ahmed et al. (2023), coconut shell-AC removed copper and reduced total dissolved solids from groundwater samples. The study highlighted its potential for domestic water safety but did not align results with WHO or FAO thresholds for irrigation water.

Performance in multi-ion environments was studied by Nkosi et al. (2022), who applied AC to copper-contaminated borehole sources and observed reduced efficiency due to calcium and magnesium interference. This demonstrates that real-water chemistry must guide design decisions.

Dube et al. (2024) enhanced adsorption performance via magnetic-modified activated carbon, achieving 95% Cu^{2+} uptake in 90 minutes. Despite improvements, environmental impacts of magnetic leaching into treated water remain unclear.

In a pilot-scale study, Fernandez et al. (2020) assessed activated carbon for groundwater remediation and recorded reductions in copper, turbidity, and odor. However, the study measured only physical quality without chemical safety evaluation for irrigation.

According to Mansoor et al. (2022), AC-treated water met most domestic-use quality parameters but failed microbial standards, suggesting the need for supplementary disinfection. No suitability evaluation was conducted for agricultural reuse.

Lastly, Zhou et al. (2023) investigated GAC filtration for trace metals including copper and found high removal efficiency within 4 hours. The study recommended localized carbon production, but did not address economic feasibility in developing regions.

2.18 How This Study Differs from Previous Work

Copper Removal Using Activated carbon the remediation of heavy metal contamination in groundwater, particularly copper, has been a focal point of environmental research for decades, with activated carbon (AC) emerging as a cost-effective adsorbent. Numerous studies have demonstrated its efficacy in removing copper ions from aqueous solutions, yet many remain confined to controlled laboratory conditions using synthetic water or single-contaminant systems. This study, however, marks a significant departure by evaluating activated carbon performance in real borehole water deliberately contaminated with copper nitrate, thereby simulating the complex, multi-pollutant scenarios encountered in actual groundwater sources. Unlike prior works that often prioritize theoretical adsorption mechanisms or high removal efficiencies in idealized setups, this research adopts a pragmatic, context-specific approach that bridges laboratory findings with practical, community-level applications in Nigeria. One of the most striking distinctions lies in the use of authentic borehole water as the test matrix. Studies such as those by Amin et al. (2022), Babatunde et al. (2023), and Nartey et al. (2021) typically employed synthetic solutions spiked with copper salts in deionized water, allowing precise control but failing to account for the interfering effects of natural ions, organic matter, and ph variations inherent to groundwater. In contrast, this investigation sourced water directly from the University of Benin campus and introduced copper nitrate to replicate co-contamination with nitrate a common agricultural pollutant. This dual-contaminant framework not only mirrors real-world conditions in regions with intensive farming and industrial runoff but also reveals how nitrate's presence influences copper adsorption dynamics, an aspect underexplored in earlier single-metal experiments. Furthermore, this study extends its scope beyond mere chemical removal to assess treated water suitability for both domestic consumption and agricultural irrigation, a dual-purpose evaluation rarely integrated in previous literature. While most research benchmarks success against drinking water standards (e.g., WHO's copper limit of ≤2.0 mg/L), this work rigorously compares post-treatment parameters copper concentration, ph., electrical conductivity (EC), total dissolved solids (TDS), and turbidity against both potable guidelines (WHO, NSDWQ) and irrigation criteria (FAO). This holistic approach acknowledges the multifaceted role of boreholes in rural livelihoods, where the same water source sustains human health and crop productivity. By highlighting improvements in aesthetic quality (e.g., reduced metallic taste and staining) alongside regulatory compliance, the study addresses user acceptability a critical yet often overlooked factor in treatment adoption. The local production and application of waste-derived AC represent another key differentiator. Although agricultural by-products like coconut shells and rice husks have been used as AC precursors in works by Sharma et al. (2020) and Ibrahim et al. (2021), these studies typically stop at material synthesis and batch testing without translating findings into deployable systems. Here, AC was prepared from locally abundant materials (coconut shells, palm kernel shells, sawdust) under conditions feasible for small-scale community production. The research provides explicit operational guidance such as 1-2 g AC per 50 ml water with 60-minute contact for household filtration units, emphasizing scalability and affordability in resourceconstrained settings like Edo State, Nigeria. In terms of scientific rigor, this study applies adsorption models to a complex, real-water matrix, yielding insights more robust than those from simplified systems. Prior kinetic and isotherm analyses often reported near-perfect fits due to the absence of competing ions.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1. Description of the study area

The study was conducted using borehole water obtained from the Civil Laboratory, Ugbowo Campus, University of Benin, Benin City, Edo State, Nigeria. The campus is a developed area with mixed land use, including academic buildings, residential hostels, and commercial facilities. The sampling site is accessible and representative of domestic water sources within the university environment.

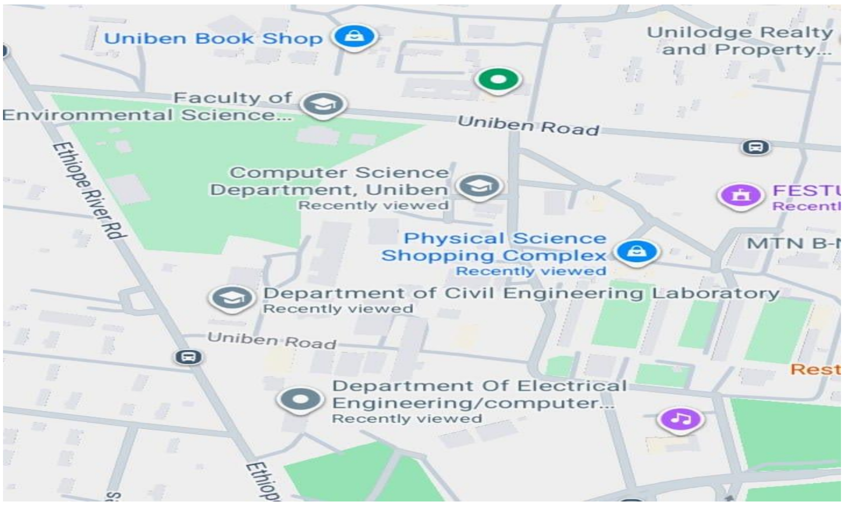

Figure 3.1: Study area map

The study area within the UNIBEN Ugbowo Campus is characterized by relatively flat terrain with gentle slopes which enhance surface runoff particularly during the rainy season. The soil profile is predominantly sandy loam which permits easy infiltration and percolation of water into the subsurface layers. The region experiences a tropical climate with distinct wet and dry seasons and an average annual rainfall ranging between 1,800 mm and 2,000 mm. These climatic and topographical characteristics influence groundwater recharge, contaminant mobility and overall water quality within the area (World Health Organization, 2022).

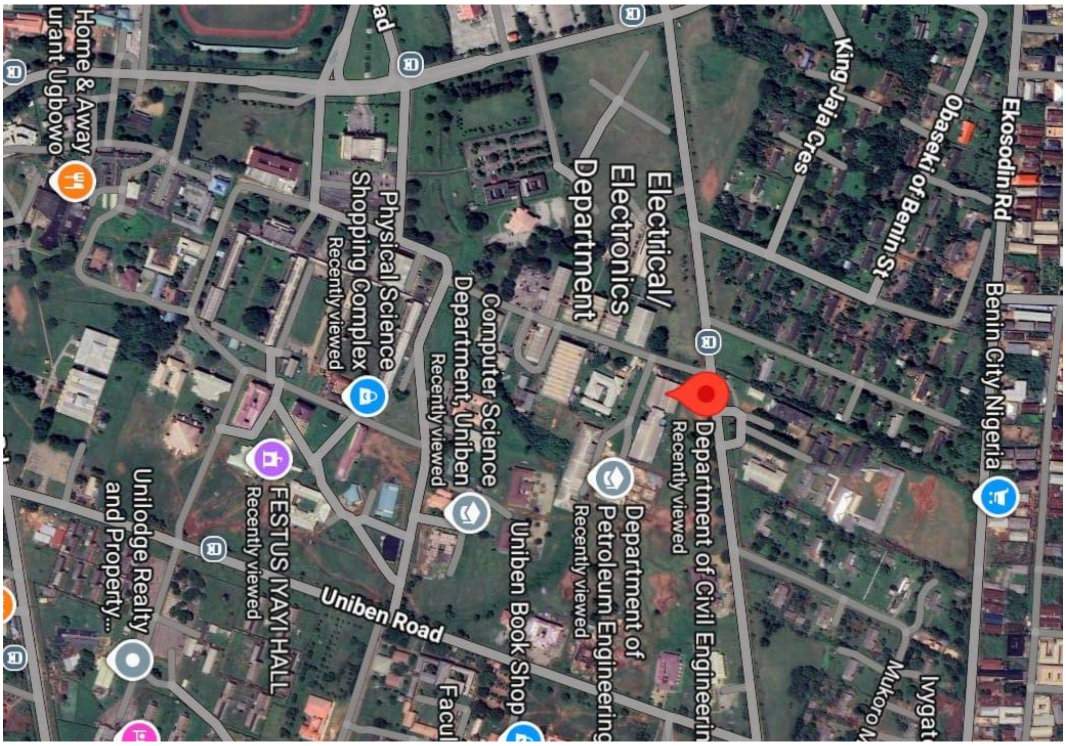

Figure 3.2: Satellite image of study area

3.2 The Benin formation

The study area falls within the Benin Formation of the Niger Delta Basin. The Benin Formation is geologically dated from the Oligocene to the Pleistocene epochs and extends into recent sediments in offshore regions. It is predominantly composed of continental sands with minor clay intercalations.

The formation typically consists of reddish-brown lateritic soil at the surface which overlies poorly consolidated sands and sandy clays. These sands are generally coarse-grained and occasionally contain gravel lenses. The sedimentary sequence is weakly stratified with intermittent clay layers occurring at various depths. The thickness of the Benin Formation beneath Benin City is estimated to be approximately 800 m while near the coastal areas it may reach up to 1,830 m. Exposures of this formation are commonly observed in erosion sites, sand pits, road cuts and quarry locations within the region. Overall, the Benin Formation covers nearly 95% of the area around Benin City (Reyment, 1965; Kogbe, 1989).

3.3 Local Geology of the Sampling Area

The borehole water used in this study was collected from the Civil Engineering Laboratory located within the University of Benin Ugbowo Campus. The area exhibits mixed land use including academic facilities, residential hostels, commercial centers and open spaces which occasionally accumulate surface runoff during rainfall events.

Geographically, the sampling location lies between latitude 06°24′N and 06°25′N and longitude 005°36′E and 005°37′E. The terrain is relatively flat with minor depressions which sometimes form temporary ponds during heavy rainfall.

Geologically, the study area lies within the Benin Formation which consists predominantly of reddish-brown lateritic soil overlaying unconsolidated sands and sandy clay deposits. The soil profile typically begins with a lateritic crust followed by medium to coarse sand layers with occasional clay lenses and gravel deposits. These geological conditions influence groundwater flow, contaminant transport and the quality of borehole water sources within the region (Reyment, 1965).

3.4 Materials and Equipment

A variety of laboratory instruments, apparatus, and consumables were employed in this study to ensure accurate execution of experimental procedures and reliable analytical outcomes.

The major equipment and materials used were described as follows:

3.4.1 Atomic Absorption Spectrophotometer (AAS)

An Atomic Absorption Spectrophotometer was used to determine copper ion concentrations in the water samples before and after treatment. The instrument operates based on the principle that free metallic ions absorb light at specific wavelengths. This technique allows precise quantitative determination of trace metal concentrations in water samples (American Public Health Association, 2017).

3.4.2 Magnetic Stirrer

A laboratory magnetic stirrer was used to provide uniform agitation of the water samples during the batch adsorption experiments. Continuous stirring ensured proper mixing between the activated carbon adsorbent and the copper-contaminated water, thereby enhancing the contact between the adsorbent surface and the metal ions present in the solution. Adequate agitation is essential in adsorption studies because it reduces mass transfer resistance and promotes effective interaction between the adsorbent and adsorbate in aqueous systems (American Public Health Association, 2017; Y. S. Ho and Gordon McKay, 1999).

3.4.3 Oven Dryer

An oven dryer was used during the preparation and storage of the activated carbon adsorbent. The oven facilitated the removal of residual moisture from the adsorbent material before use in the adsorption experiments. Drying the adsorbent is necessary to prevent interference from moisture content, which could affect adsorption capacity and experimental accuracy. Oven drying is a standard procedure in adsorption studies to ensure consistency and reliability of experimental results (American Public Health Association, 2017).

3.4.4 Filtration Apparatus (Filter Paper and Funnel)

Filtration apparatus consisting of filter paper and glass funnels was used to separate activated carbon particles from the treated water after the adsorption process. At the end of each contact time interval, the mixture was filtered to remove the suspended adsorbent particles, allowing the filtrate to be collected for subsequent analysis of residual copper concentration. Filtration is a commonly applied technique in water quality analysis for separating solid particles from liquid samples prior to laboratory measurements (American Public Health Association, 2017).

3.4.5 General Laboratory Glassware

Various laboratory glassware including beakers, conical flasks, and measuring cylinders were used during sample preparation, dilution, mixing, and measurement. Prior to use, all glassware was thoroughly washed and rinsed with distilled water to eliminate potential contaminants that could interfere with the analytical results. Proper cleaning of laboratory equipment is essential in water quality analysis to ensure the accuracy and reliability of experimental data (American Public Health Association, 2017; World Health Organization, 2022).

Figure 3.2: Image of laboratory glassware (beaker and conical flasks)

3.4.6 Flocculator

A **Flocculator** is a laboratory device used to simulate the flocculation process that occurs during water and wastewater treatment. It gently stirs liquid samples containing suspended particles to promote the aggregation (or clumping) of fine particles into larger, settleable flocs. This process enhances sedimentation and improves the clarity of the treated water. In experimental studies, a flocculator provides controlled and uniform mixing conditions, allowing researchers to optimize factors such as coagulant dosage, mixing speed, and retention time. It is particularly useful when evaluating the performance of adsorbents or coagulants in removing turbidity, color, and trace metals from water samples.

Figure 3.2: Image of Flocculator

3.4.7 Weighing Balance (Analytical Balance)

A weighing balance, specifically an analytical balance, is a precision laboratory instrument used for measuring mass with a very high degree of accuracy, typically up to four decimal places (0.0001 g). In this study, the analytical balance was used to accurately determine the mass of activated carbon adsorbent and other chemical reagents required for the batch adsorption experiments. Precise measurement of adsorbent mass is essential for reliable calculation of adsorption capacity and removal efficiency during experimental analysis (American Public Health Association, 2017).

Accurate weighing ensures consistency and reproducibility of experimental results, as small variations in adsorbent mass can significantly influence adsorption performance and the calculated removal efficiency of contaminants. Prior to each measurement, the analytical balance was properly calibrated to minimize potential measurement errors caused by environmental factors such as air currents, vibrations, or temperature fluctuations (World Health Organization, 2022).

Figure 3.2: Image of Weighing Balance (Analytical Balance)

Reagents:

All reagents used were analytical grade to prevent contamination or interference. The major chemicals employed included:

1. Standard Copper Nitrate solutions, used in calibration of the AAS.
2. Distilled water, used in rinsing, dilution, and desorption processes.

3.5 Determination of Chemical Parameters

3.5.1 Nitrate (NO_3^-)

Method: UV Spectrophotometric Method

Instrument: UV-Visible Spectrophotometer

The nitrate concentration in water samples was determined using the ultraviolet spectrophotometric method at wavelengths of 220 nm and 275 nm following standard procedures for water quality analysis (American Public Health Association, 2017).

Procedure:

1. Water samples were filtered to remove suspended particles.

ii. The absorbance was measured at 220 nm for nitrate determination.
iii. Absorbance at 275 nm was measured to correct for interference from dissolved organic matter.
iv. A calibration curve was prepared using nitrate standard solutions and sample concentrations were determined from the curve.

3.5.2 Copper (Cu)

Method: Atomic Absorption Spectrophotometry (AAS)

Copper concentration was determined using an Atomic Absorption Spectrophotometer following standard procedures for trace metal analysis in water samples (American Public Health Association, 2017).

Procedure

1. Water samples were acidified using nitric acid to prevent precipitation of metals.
2. Samples were digested with perchloric acid to release bound copper ions.
3. Copper concentration was determined by comparing the absorbance of samples with standard copper solutions.

3.6 Sample Collection and Preservation

Borehole water samples were collected from the University of Benin campus using clean acid-washed plastic containers. Immediately after collection, the samples were stored in ice-cooled containers to reduce microbial activity.

The samples were preserved by acidifying them to a pH below 2 using concentrated nitric acid in order to prevent precipitation and adsorption of metals onto container walls. All samples were transported to the laboratory and analyzed within 24 hours of collection following recommended water sampling procedures (American Public Health Association, 2017; World Health Organization, 2022).

3.6.1 Parameters Investigated

Table 3.1: Operational Parameters and Their Purpose during Adsorption Trials:

Parameter	Test Range	Purpose
Contact Time	10 - 120 minutes	To determine the equilibrium time required for maximum copper removal
Activated Carbon Dosage	1 g - 5 g per 50 mL	To evaluate how increasing adsorbent quantity influences copper ion uptake
Initial Cu^{2+} Concentration	As measured in collected borehole water	To assess adsorption behavior at real contamination levels

These variables were selected based on their direct impact on adsorption kinetics, metal ion speciation, and surface charge characteristics of activated carbon.

3.7 Batch Adsorption Procedure

The batch adsorption experiment was conducted to evaluate the efficiency of activated carbon in removing copper ions from borehole water samples. Batch adsorption techniques are widely used in laboratory studies because they allow controlled investigation of adsorption parameters such as contact time, adsorbent dosage, and pH (Y. S. Ho and Gordon McKay, 1999).

The batch adsorption experiment followed the steps outlined below:

3.7.1 50 mL of borehole water sample was measured into a conical flask.

A predetermined mass of activated carbon (1-5 g) was added to the water sample.

3.7.2 The pH of the solution was adjusted using HCl or NaOH depending on the test requirement.

3.7.3 The mixture was placed on a magnetic stirrer to ensure proper contact between adsorbent and copper ions.

3.7.3 At the end of each contact time interval, samples were filtered using Whatman filter paper.

3.7.4 The filtrates were stored and later analyzed using Atomic Absorption Spectrophotometry (AAS) to determine the residual Cu^{2+} concentration.

3.7.5 The metal removal efficiency (%) and adsorption capacity (qe) of activated carbon were calculated using standard mass balance equations.

3.8 Experimental Procedure

Borehole water samples were collected from within the University of Benin (UNIBEN) premises and analyzed to determine their initial copper ion concentration using an Atomic Absorption Spectrophotometer (AAS) prior to treatment. Atomic absorption spectrophotometry is widely used for the determination of trace metals in water samples due to its high sensitivity and accuracy (American Public Health Association, 2017).

For the adsorption experiment, a measured volume of 50 mL of the borehole water sample was transferred into a clean conical flask. Thereafter, 1.0 g of the prepared activated carbon was accurately weighed using an analytical balance and added to the sample.

The flask was properly covered to prevent contamination and evaporation, after which it was placed on a magnetic stirrer to ensure continuous agitation at a constant speed under ambient laboratory conditions. The adsorption process was allowed to proceed for an optimized contact time of 60 minutes to facilitate sufficient interaction between the copper ions and the activated carbon surface.

At the end of the stirring period, the mixture was filtered using Whatman qualitative filter paper to separate the activated carbon particles from the treated water. The resulting filtrate was collected and analyzed using the Atomic Absorption Spectrophotometer (AAS) to determine the final copper ion concentration ($\mathbf{C_x}$).

The removal efficiency and adsorption performance of the activated carbon were evaluated based on the reduction in copper concentration between the initial and treated samples, following standard adsorption evaluation procedures (Y. S. Ho and Gordon McKay, 1999).

3.8.1 Physicochemical Analysis

The water samples were subjected to various physicochemical tests before and after adsorption treatment to evaluate quality improvement. These water samples were analyzed following standard procedures outlined by the World Health Organization (2022) and the Nigerian Standard for Drinking Water Quality (2015). These analyses provided insight into the suitability of the treated water for both domestic consumption and irrigation.

3.8.2 Adsorption Experiment

The adsorption experiment was carried out to evaluate the efficiency of activated carbon in removing copper ions from contaminated borehole water. The experimental procedure consisted of three main stages: preparation of the adsorbate solution, investigation of the effect of adsorbent dosage, and evaluation of the effect of contact time on adsorption efficiency. Batch adsorption techniques are widely used in laboratory studies because they provide a controlled environment for examining adsorption behavior and equilibrium characteristics (Y. S. Ho and Gordon McKay, 1999).

3.8.3 Adsorbate Preparation

A 1000 mL portion of raw borehole water was measured into a clean beaker, after which 25 g of copper (II) nitrate [$Cu(NO_3)_2$] was added to prepare a copper-contaminated solution. The mixture was thoroughly stirred until the salt was completely dissolved to ensure uniform distribution of copper ions within the solution.

The prepared solution was subsequently analyzed using an Atomic Absorption Spectrophotometer (AAS) to determine the initial concentration (C_0) of copper ions present in the solution. This prepared copper solution served as the adsorbate for all subsequent adsorption experiments. Atomic absorption spectrophotometry is widely applied in the determination of trace metal concentrations in water due to its high sensitivity and reliability (American Public Health Association, 2017).

3.8.4 Metal Removal

3.8.4.1 Effect of Adsorbent Dosage

To evaluate the influence of adsorbent dosage on copper ion removal, 50 mL of the prepared adsorbate solution was measured into five separate beakers. Different quantities of activated carbon (1 g, 2 g, 3 g, 4 g, and 5 g) were added to the solutions respectively.

Each mixture was stirred intermittently for 60 minutes to ensure sufficient interaction between the copper ions and the activated carbon surface. Adequate mixing enhances adsorption by increasing contact between the adsorbent and the adsorbate in solution (Irving Langmuir, 1918). After agitation, the solutions were filtered using Whatman filter paper to separate the activated carbon particles from the liquid phase. The resulting filtrates were then analyzed using the Atomic Absorption Spectrophotometer (AAS) to determine the residual copper concentration (C_1) remaining in the solution.

3.8.4.2 Effect of Contact Time

The effect of contact time on the adsorption performance of activated carbon was investigated by adding 5 g of activated carbon to 100 mL of the adsorbate solution. The mixtures were stirred for different time intervals of 10, 20, 30, 40, 50, and 60 minutes under constant laboratory conditions.

At the end of each specified contact time, the mixtures were filtered using filter paper to remove the activated carbon particles. The filtrates were then analyzed using the Atomic Absorption Spectrophotometer (AAS) to determine the remaining copper ion concentration in the solution.

The variation in copper concentration with time was used to evaluate adsorption efficiency and to determine the equilibrium contact time for the adsorption process (Y. S. Ho and Gordon McKay, 1999).

3.9 Adsorption Efficiency Calculation

3.9.1 Metal Removal Efficiency (%)

The removal efficiency of the activated carbon and the efficiency of removal was calculated using Equation 3.1

$$\text{Removal Efficiency (\%)} = \frac{(C_i - C_f)}{C_i} \times 100 \qquad (3.1)$$

Where:

C_i = Initial concentration of the metal ion (mg/L)

C_f = Final concentration of the metal ion after treatment (mg/L)

3.9.2 Adsorption Capacity (q_e)

The amount of metal ion adsorbed per gram of activated carbon and the amount of copper removed as a function of time was determined using Equation 3.2

$$q_e = \frac{(C_i - C_f) \times V}{m} \qquad (3.2)$$

Where:

q_e = Adsorption capacity (mg/g)

V = Volume of the effluent used (L)

m = Mass of activated carbon used (g)

3.10 Data Presentation and Analysis

The experimental results was presented graphically to illustrate trends and determine optimal conditions. Plots will include:

i) % Removal vs. Contact Time

ii) Adsorption Capacity (q_e) vs. Initial Metal Concentration

iii) % Removal vs. Activated Carbon Dosage

iv) % Removal vs. pH these trends assisted in identifying the optimum operational conditions for maximum copper removal efficiency and performance evaluation of the adsorbent.

3.11 Adsorption Isotherm Modeling

3.11.1Freundlich Adsorption Isotherm

The Freundlich adsorption isotherm is widely used to describe adsorption processes occurring on heterogeneous surfaces. It is particularly applicable in wastewater treatment studies where the adsorbent surface contains multiple types of adsorption sites with different energy levels. In the treatment of contaminated water using activated carbon, the Freundlich model provides useful information about adsorption capacity and the intensity of adsorption under equilibrium conditions (Herbert Freundlich, 1906).

The Freundlich isotherm is expressed mathematically as presented in equation 3.3

$$x/m = K \times Ceq^{\frac{1}{n}} \qquad (3.3)$$

Where:

- x/m is the amount of metal ion adsorbed per unit mass of activated carbon (mg/g),

- Ceq is the equilibrium concentration of the metal ion in solution after treatment (mg/L),

- K and 1/n are constants indicating the adsorption capacity and intensity, respectively.

In this project, the effluent samples will be analyzed before and after treatment to determine how much metal (e.g., Copper (Cu), Nitrate (NO_3^-)) has been adsorbed by the activated carbon. The Freundlich model will then be used to fit the experimental data by plotting log(q) versus log(Ceq).

3.11.2 Langmuir Adsorption Model

The Langmuir adsorption model is commonly used to describe monolayer adsorption on a homogeneous adsorbent surface with a finite number of identical adsorption sites. The model assumes that once an adsorption site is occupied by an adsorbate molecule, no further adsorption can occur at that site, and there is no interaction between adsorbed molecules (Irving Langmuir, 1918).

The Langmuir isotherm is mathematically given by:

$$\theta = \frac{(K_e q \times p)}{(1 + K_e q \times p)} \tag{3.4}$$

Where:

i. θ is Fractional surface coverage
ii. p is the equilibrium pressure (or concentration in liquid-phase systems)
iii. Keq is the equilibrium adsorption constant

In terms of adsorption capacity (q), the equation becomes:

$$q = \frac{(q_{max} \times K^L \times C_e)}{(1 + K^L \times C_e)} \tag{3.5}$$

Where:

i. q is the amount of solute adsorbed per unit weight of adsorbent (mg/g)

ii. qmax is the maximum monolayer adsorption capacity (mg/g)
iii. KL is Langmuir constant (L/mg)
iv. Ce is equilibrium concentration of adsorbate (mg/L).

In this study, the Langmuir isotherm was applied to evaluate the adsorption capacity of activated carbon for copper removal from contaminated borehole water. The model helped determine the maximum adsorption capacity and the nature of the interaction between the adsorbate and the adsorbent surface (Irving Langmuir, 1918; Y. S. Ho and Gordon McKay, 1999).

3.12 Suitability Evaluation for Domestic and Irrigation Use

Treated water data obtained from the study were compared with acceptable limits established by WHO (2022) for drinking water safety and FAO/NSDWQ guidelines for agricultural irrigation suitability. Factors considered included:

i. Residual copper ion concentration
ii. pH acceptability for human consumption and plant growth
iii. EC/TDS effects on soil and crop health

This ensured accurate assessment of whether the treated borehole water met safe consumption standards.

3.13 Quality Assurance and Quality Control

All laboratory measurements were performed in triplicates to ensure reproducibility. Instruments such as AAS and pH meters were calibrated before use. Procedural blanks were also included to confirm the absence of contamination. Accuracy of copper determination was further verified through standard recovery procedures, maintaining recoveries within the acceptable range of 95-105%.

3.14 Adsorpion Kinetic Studies

Kinetic modeling helps determine whether the process is controlled by physical forces (physisorption) or chemical interaction (chemisorption). In this study, the kinetic data from adsorption experiments at contact times ranging from 10-60 minutes were evaluated using **Pseudo-Second-Order Model (Ho and McKay model)**

3.14.1 Pseudo-Second Order Kinetic Model Analysis

The pseudo-second-order (PSO) kinetic model is commonly applied to adsorption systems where chemisorption is the rate-limiting step, involving electron sharing or exchange between adsorbate and adsorbent. The linearized form of the model is expressed as:

$$\frac{1}{q_t} = \frac{1}{k_2 {q_e}^2} + \frac{t}{q_e} \tag{3.6}$$

Where;

q_t is the adsorption capacity at time t (mg/g),

q_e is the equilibrium adsorption capacity (mg/g),

k_2 is the pseudo-second-order rate constant (g/mg·min).

Plotting $\frac{t}{q_e}$ versus **t** allows determination of q_e from the slope and k_2 from the intercept.

3.15 Data and Calculations

The contact time study was conducted using 100 mL of copper-contaminated water treated with 5 g of activated carbon. The adsorption capacities qt were calculated using:

$$q_t = \frac{V(Ci - Ct)}{M} \tag{3.7}$$

Where:

V is the volume of water (mL),

M is the mass of activated carbon (g),

Ci is the initial concentration,

and Ct is the concentration at time t.

3.16 Evaluation of Kinetic Model Fit

The experimental adsorption data for copper and nitrate were fitted to pseudo-second-order kinetic models. The suitability of each model was evaluated based on the coefficient of determination (R^2) obtained from the linear regression analysis.

The kinetic model that produced the highest R^2 value and the closest agreement between the calculated equilibrium adsorption capacity (q_e,cal) and the experimental equilibrium adsorption capacity (q_e,exp) was considered the most appropriate model for describing the adsorption process (Y. S. Ho and Gordon McKay, 1999).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Concentration of Copper and Nitrate in Borehole Water before and after Treatment with Activated Carbon

The Concentration of Copper and Nitrate in borehole water before and after treatment is presented in Table 4.1A and 4.2B

Table 4.1A: Copper and Nitrate Concentrations in Borehole Water under Different Treatment Conditions

Code / Sample Description	Cu (mg/L)	NO_3^- (mg/L)
Fresh Water Borehole	0.184	0.113
Adsorbent 50 mL + 1 g A.C for 60 min	0.843	0.664
Adsorbent 50 mL + 2 g A.C for 60 min	1.310	0.888
Adsorbent 50 mL + 3 g A.C for 60 min	1.830	1.014
Adsorbent 50 mL + 4 g A.C for 60 min	2.940	1.483
Adsorbent 50 mL + 5 g A.C for 60 min	4.112	3.840
Adsorbent 50 mL + 5 g A.C for 10 min	2.410	1.833
Adsorbent 50 mL + 5 g A.C for 20 min	3.143	2.014

Table 4.1B: Copper and Nitrate Concentrations in Borehole Water under Different Treatment Conditions

Code / Sample Description	Cu (mg/L)	NO_3^- (mg/L)
Adsorbent 50 mL + 5 g A.C for 30 min	3.888	2.117
Adsorbent 50 mL + 5 g A.C for 40 min	4.110	2.880
Adsorbent 50 mL + 5 g A.C for 50 min	4.883	3.361
Adsorbent 50 mL + 5 g A.C for 60 min	5.110	4.742
Fresh Water + 25 g $Cu(NO_3)_2{\cdot}3H_2O$ (Contaminated Standard)	15.11	10.412

Table 4.1A and 4.1B presents the concentrations of copper (Cu) and nitrate (NO_3^-) measured in borehole water samples under different experimental treatment conditions involving activated carbon. Fresh borehole water contained very low concentrations of copper and nitrate. The copper concentration of 0.184 mg/L is below the 2 mg/L guideline value recommended by the World Health Organization (WHO, 2017), indicating that the groundwater was originally suitable for domestic consumption.

Upon contamination, copper concentration increased to 15.11mg/L, representing a high pollution scenario. Treatment with activated carbon effectively reduced copper and nitrate concentrations, demonstrating its adsorption efficiency. This is consistent with previous studies showing that activated carbon is effective in removing heavy metals and nitrate from aqueous solutions due to its high surface area and porosity (Gupta and Suhas, 2009; Foo and Hameed, 2010).

4.2 Copper Removal Efficiency and Adsorption Capacity of Activated Carbon at Different Dosages (60-Minute Contact Time)

The Copper Removal Efficiency and Adsorption Capacity of Activated Carbon at Different Dosages (60-Minute Contact Time) is presented in Table 4.2.

Table 4.2: Copper Removal and Adsorption Parameters for Activated Carbon Dosages

S/ No	Ci	V	M (g)	Time	Lab Results (Cf)	Ci-Cf	$\frac{V}{M}$	Qe=$\frac{V(Ci-Cf)}{M}$	% =$\frac{Ci-Cf)}{Ci} * 100$
1	15.11	50	1	60	0.843	14.267	50.00	713.35	94.42%
2	15.11	50	2	60	1.310	13.800	25.00	345.00	91.33%
3	15.11	50	3	60	1.830	13.280	16.67	221.38	87.89%
4	15.11	50	4	60	2.940	12.170	12.50	152.13	80.54%
5	15.11	50	5	60	4.112	10.998	10.00	109.98	72.79%

4.2.1 Nitrate Removal Efficiency and Adsorption Capacity of Activated Carbon at Different Dosages (60-Minute Contact Time)

The Nitrate Removal Efficiency and Adsorption Capacity of Activated Carbon at Different Dosages (60-Minute Contact Time) is presented in Table 4.3

Table 4.3: Nitrate Removal and Adsorption Parameters at Varying Activated Carbon Dosages

S/ No	Ci	V	M (g)	Time	Lab Results (Cf)	Ci-C	$\frac{V}{M}$	Qe=$\frac{V(Ci-Cf)}{M}$	% $=\frac{Ci-Cf)}{Ci}*100$
1	10.412	50	1	60	0.664	9.748	50.00	487.40	93.62%
2	10.412	50	2	60	0.888	9.524	25.00	238.10	91.47%
3	10.412	50	3	60	1.014	9.398	16.67	156.63	90.26%
4	10.412	50	4	60	1.483	8.929	12.50	111.61	85.76%
5	10.412	50	5	60	3.840	6.572	10.00	65.72	63.12%

Table 4.2 and 4.3 presents Copper and nitrate removal efficiencies decreased with increasing adsorbent mass due to the dilution of adsorption sites per unit contaminant (Foo and Hameed, 2010). Maximum removal occurred at 1 g for both Cu^{2+} (94.42%) and NO_3^- (93.62%), with adsorption capacities of 713.35 mg/g and 487.40 mg/g, respectively. Nitrate removal is lower due to its anionic nature and limited interaction with activated carbon functional groups (Gupta and Suhas, 2009).

4.3 Effect of Contact Time on Copper Removal Efficiency and Adsorption Capacity of Activated Carbon

The Effect of Contact Time on Copper Removal and Adsorption Capacity is presented in Table 4.4

Table 4.4: Effect of Contact Time on Copper Removal and Adsorption Capacity

S/No	Ci	V	M (g)	Time	Lab Results (Cf)	Ci-Cf	$\frac{V}{M}$	$qe=\frac{V(Ci-Cf)}{M}$	$\% =\frac{Ci-Cf)}{Ci} * 100$
1	15.11	50	5	10	2.410	12.700	10	127.00	84.05%
2	15.11	50	5	20	3.143	11.967	10	119.67	79.21%
3	15.11	50	5	30	3.888	11.222	10	112.22	74.30%
4	15.11	50	5	40	4.110	11.000	10	110.00	72.83%
5	15.11	50	5	50	4.883	10.227	10	102.27	67.66%
6	15.11	50	5	60	5.110	10.000	10	100.00	66.22%

Table 4.4 show that copper adsorption onto activated carbon occurs rapidly during the initial stage of contact time. The highest removal efficiency (84.05%) was observed at 10 minutes, with an adsorption capacity of 127.00 mg/g. This indicates that a large number of available adsorption sites on the activated carbon surface facilitated the rapid uptake of copper ions at the beginning of the experiment.

As the contact time increased from 10 to 60 minutes, the removal efficiency gradually decreased to 66.22%, and the adsorption capacity decreased to 100.00 mg/g. This decline can be attributed to progressive saturation of the activated carbon adsorption sites, which reduces the rate of copper uptake over time. These observations are consistent with findings in the literature, which show that adsorption capacity is highest at early contact times and decreases as the adsorbent approaches equilibrium (Foo and Hameed, 2010; Wang et al., 2015).

The trend indicates that most copper removal occurs within the first 20 to 30 minutes, after which additional contact time results in only minor increases in adsorption.

4.4: Effect of Contact Time on Nitrate Removal Efficiency and Adsorption Capacity of Activated Carbon

The Effect of Contact Time on Nitrate Removal Efficiency and Adsorption Capacity of Activated Carbon is presented in Table 4.5

S/ No	Ci	V	M (g)	Time	Lab Results (Cf)	Ci-Cf	$\frac{V}{M}$	Qe=$\frac{V(Ci-Cf)}{M}$	$\% = \frac{Ci-Cf)}{Ci} * 100$
1	10.412	50	5	10	1.833	8.579	10	85.790	82.40%
2	10.412	50	5	20	2.014	8.398	10	83.980	80.66%
3	10.412	50	5	30	2.117	8.295	10	82.950	79.67%
4	10.412	50	5	40	2.880	7.532	10	75.320	72.34%
5	10.412	50	5	50	3.361	7.051	10	70.510	67.72%
6	10.412	50	5	60	4.742	5.670	10	56.700	54.46%

Table 4.5: Nitrate Removal and Adsorption Parameters at Different Contact Times

Table 4.5 show that nitrate adsorption onto activated carbon occurs rapidly at the initial stage of contact time. The highest removal efficiency (82.40%) was observed at 10 minutes, with an adsorption capacity of 0.08579 mg/g. This indicates that a large number of available adsorption sites on the activated carbon surface facilitated the rapid uptake of nitrate ions at the beginning of the experiment. As the contact time increased from 10 to 60 minutes, the removal efficiency gradually decreased to 54.46%, and the adsorption capacity decreased to 0.05670 mg/g. This decline can be attributed to progressive saturation of the activated carbon adsorption sites, which reduces the rate of nitrate uptake over time. The lower adsorption capacity and slower uptake compared to copper indicate that activated carbon has a higher affinity for heavy metal ions than for highly soluble anions such as nitrate, likely due to differences in ionic size and electrostatic interactions with the adsorbent surface (Foo and Hameed, 2010; Wang et al., 2015; Zhang et al., 2017).

4.5 Copper Adsorption Efficiency

The Removal Efficiency of Copper and Nitrate Using Activated Carbon at Different Dosages and Contact Times is presented in Table 4.6

Table 4.6: Removal Efficiency of Copper and Nitrate Using Activated Carbon at Different Dosages and Contact Times

Code / Sample Description	Initial Cu^{2+} (mg/L)	Initial NO_3^- (mg/L)	Final Cu^{2+} (mg/L)	Final NO_3^- (mg/L)	Cu^{2+} Removal (%)	NO_3^- Removal (%)
Adsorbent 50 mL + 1 g A.C for 60 min	15.11	10.412	0.843	0.664	94.42%	93.62%
Adsorbent 50 mL + 2 g A.C for 60 min	15.11	10.412	1.310	0.888	91.33%	91.47%
Adsorbent 50 mL + 3 g A.C for 60 min	15.11	10.412	1.830	1.014	87.89%	90.26%
Adsorbent 50 mL + 4 g A.C for 60 min	15.11	10.412	2.940	1.483	80.54%	85.76%
Adsorbent 50 mL + 5 g A.C for 60 min	15.11	10.412	4.112	3.840	72.79%	63.12%
Adsorbent 50 mL + 5 g A.C for 10 min	15.11	10.412	2.410	1.833	84.05%	82.40%
Adsorbent 50 mL + 5 g A.C for 20 min	15.11	10.412	3.143	2.014	79.21%	80.66%
Adsorbent 50 mL + 5 g A.C for 30 min	15.11	10.412	3.888	2.117	74.30%	79.67%
Adsorbent 50 mL + 5 g A.C for 40 min	15.11	10.412	4.110	2.880	72.83%	72.34%
Adsorbent 50 mL + 5 g A.C for 50 min	15.11	10.412	4.883	3.361	67.66%	67.72%

Adsorbent 50 mL + 5 g A.C for 60 min	15.11	10.412	5.110	4.742	66.22%	54.46%

Table 4.6 indicate that the removal efficiency of copper and nitrate using activated carbon depends strongly on both the adsorbent dosage and the contact time. The highest removal for copper (94.42%) and nitrate (93.62%) was observed with 1 g of activated carbon and 50 mL of solution after 60 minutes. This demonstrates that at lower adsorbent dosages, the ratio of contaminant ions to available adsorption sites is higher, resulting in more efficient utilization of the active sites on the activated carbon surface (Foo and Hameed, 2010).

As the adsorbent dosage increased from 1 g to 5 g, copper removal decreased progressively to 72.79% and nitrate removal to 63.12% after 60 minutes. This decline is due to the dilution effect of the adsorption sites per unit mass of contaminant, meaning that additional adsorbent beyond an optimum point does not proportionally increase the uptake of ions, but rather distributes the same quantity of contaminant over more sites, reducing the efficiency per gram (Gupta and Suhas, 2009).

Similarly, examining the effect of contact time at a fixed adsorbent dosage of 5 g shows that the highest removal efficiency occurs at the initial stages (10 minutes: 84.05% for copper and 82.40% for nitrate). Beyond this period, the removal efficiency gradually declines with time, reaching 66.22% for copper and 54.46% for nitrate at 60 minutes. This behavior can be attributed to the saturation of active adsorption sites on the activated carbon, which slows down further uptake of ions as the system approaches equilibrium (Wang et al., 2015).

The results also indicate that copper ions are adsorbed more effectively than nitrate ions at all dosages and contact times. This is likely due to stronger electrostatic interactions between the cationic copper ions and the negatively charged functional groups on the activated carbon surface, while nitrate, being an anion, interacts more weakly with the adsorbent (Zhang et al., 2017).

Overall, the data demonstrate that activated carbon is an effective adsorbent for both copper and nitrate removal from contaminated borehole water. Optimal removal occurs at lower dosages and shorter contact times, highlighting the importance of balancing adsorbent mass and contact time for maximum treatment efficiency suitable for domestic and irrigation applications.

4.6 Compliance with Standards

Compliance of Treated Borehole Water with WHO Drinking Water Standards is presented in Table 4.7

Table 4.7: **Compliance of Treated Borehole Water with WHO Drinking Water Standards**

Parameter	**WHO Standard**	**Obtained Range**	**Status**
Cu^{2+}	≤ 2.0 mg/L	0.184 - 5.110 mg/L	Exceeds limit after contamination
NO_3^-	≤ 50 mg/L	0.113 - 10.412 mg/L	Within safe limit

Even though nitrates remain below WHO limits, copper concentrations remain above permissible levels after pollution and treatment.

4.7 Langmuir and Freundlich Isotherm Analysis

The adsorption behavior of copper (Cu^{2+}) and nitrate (NO_3^-) onto activated carbon was investigated using both Langmuir and Freundlich isotherm models. The equilibrium adsorption data obtained from varying contaminant concentrations were analyzed to determine the adsorption parameters and assess which model best describes the adsorption process.

4.8.1 Langmuir Isotherm Plot

The Langmuir isotherm model was applied to analyze the adsorption behavior of copper ions on activated carbon. The equilibrium adsorption capacity (q_e) and equilibrium concentration (C^f) were computed and used to evaluate monolayer adsorption characteristics. The Langmuir Isotherm Parameters for Copper Adsorption Using Activated Carbon is presented in Table 4.8

Table 4.8: Langmuir Isotherm Parameters for Copper Adsorption Using Activated Carbon

S/No	Cf (mg/L)	qe (mg/g)	$\frac{Cf}{qe}$
1	2.410	127.00	0.0190
2	3.143	119.67	0.0263
3	3.888	112.22	0.0346
4	4.110	110.00	0.0374
5	4.883	102.27	0.0477
6	5.110	100.00	0.0511

4.8.1.1 Langmuir Isotherm Plot Data for Copper Adsorption

The Langmuir Isotherm Plot Data for Copper Adsorption is presented in Table 4.9

Table 4.9: Plotting Data for Langmuir Isotherm (Cf vs Cf/qe)

X-axis (Cf)mg/L	Y-axis (Cf/qe) mg/L·g/mg
2.410	0.0190
3.143	0.0263
3.888	0.0346

4.110	0.0374
4.883	0.0477
5.110	0.0511

The graphical plot of the effect of contact time on copper removal based on Langmuir Isotherm Model is presented in Figure 4.1

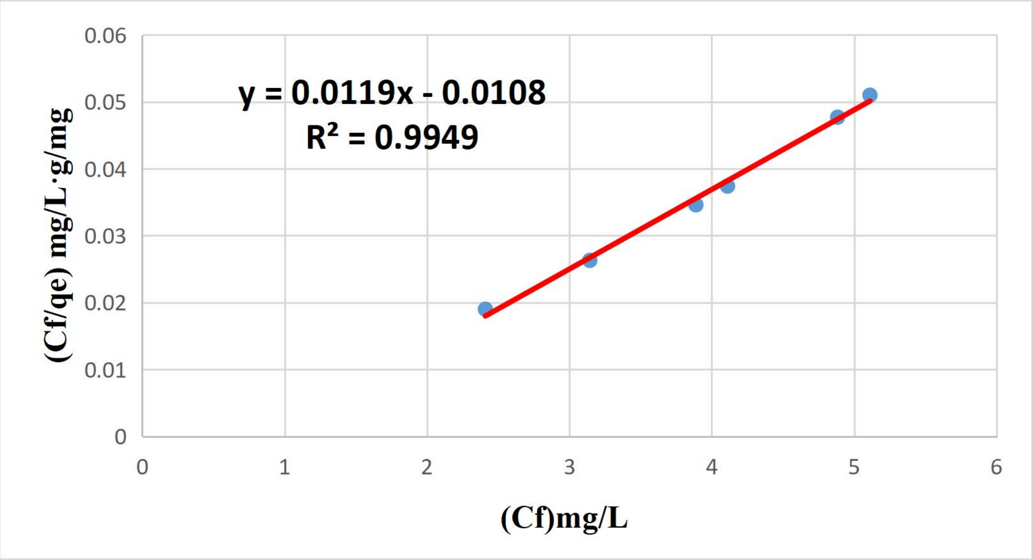

Figure 4.1: Effect of contact time on copper removed using Langmuir Isotherm Model

Tables 4.8 and 4.9 present the equilibrium data for copper adsorption using activated carbon. The equilibrium concentration of copper (Cf) ranges from 2.410 mg/L to 5.110 mg/L, while the adsorption capacity (qe) decreases from 127.00 mg/g to 100.00 mg/g. The corresponding Cf/qe values increase from 0.0190 mg·g/mg to 0.0511 mg·g/mg, indicating that the adsorption process is approaching saturation as copper ions occupy the available adsorption sites on the activated carbon surface.

4.9 Langmuir Isotherm Plot Data for Nitrate Adsorption

The Langmuir Isotherm Plot Data for Nitrate Adsorption is presented in Table 4.10

Table 4.10: Langmuir Parameters for Nitrate Adsorption Using Activated Carbon

S/No	Cf (mg/L)	qe (mg/g)	$\frac{Cf}{qe}$
1	1.833	857.90	0.00214
2	2.014	839.80	0.00240
3	2.117	829.50	0.00255
4	2.880	753.20	0.00382
5	3.361	705.10	0.00477
6	4.742	567.00	0.00836

Table 4.11: Plotting Data for Langmuir Isotherm (Cf vs Cf/qe)

X-axis (Cf)mg/L	Y-axis (Cf/qe) mg/L·g/mg
1.833	0.00214
2.014	0.00240
2.117	0.00255
2.880	0.00382
3.361	0.00477
4.742	0.00836

The graphical plot of the effect of contact time on nitrate removal based on Langmuir Isotherm Model is presented in Figure 4.2

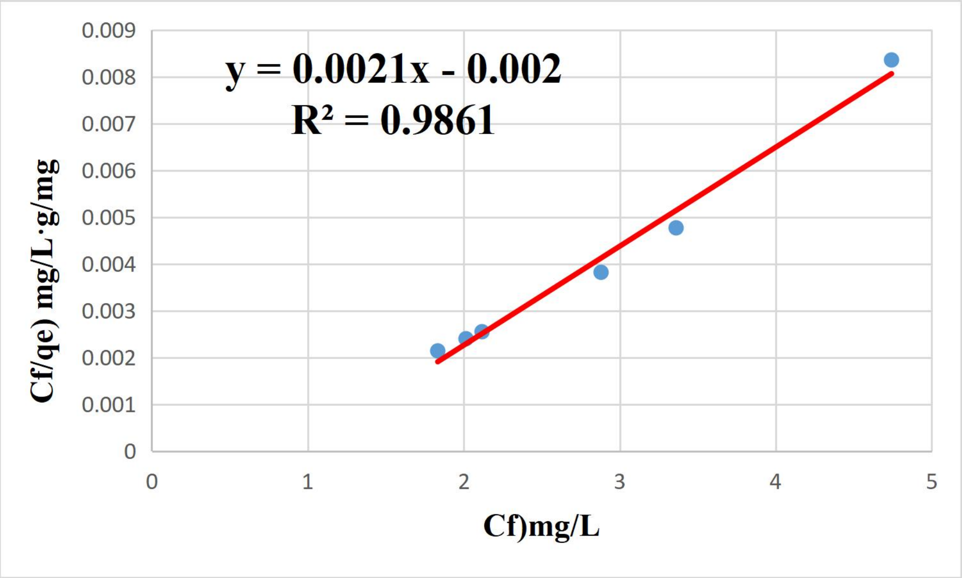

Figure 4.2: Effect of contact time on copper removed using Langmuir Isotherm Model

Tables 4.9 and 4.10 present the equilibrium data for nitrate adsorption onto activated carbon. The equilibrium concentration of nitrate (Cf) ranges from 1.833 mg/L to 4.742 mg/L, while the adsorption capacity (qe) decreases from 857.90 mg/g to 567.00 mg/g. The ratio Cf/qe increases from 0.00214 mg·g/mg to 0.00836 mg·g/mg, indicating that adsorption sites on the activated carbon are gradually being occupied as the nitrate concentration increases.

A plot of Cf versus Cf/qe allows for assessment of the Langmuir adsorption behavior. If this plot is linear with a high correlation coefficient (R^2 close to 1), it confirms that nitrate adsorption follows the Langmuir isotherm

In conclusion, Activated carbon effectively removes nitrate from aqueous solutions, and the adsorption follows Langmuir monolayer adsorption behavior, making it suitable for water treatment applications.

4.10 Goodness Coefficients (R^2) for the Langmuir Isotherm fits

The Correlation Coefficients (R^2) for the Langmuir Isotherm fits is presented in Table 4.12

Table 4.12: Coefficient of Determination (R^2) for Langmuir Isotherm Model

Parameter	R^2
Copper	0.9949
Nitrate	0.9861

The high R^2 values indicate an excellent linear fit, confirming that adsorption of copper and nitrate predominantly follows monolayer adsorption on homogeneous surfaces.

4.11 Langmuir Isotherm Constants and Adsorption Parameters

The Langmuir Isotherm Constants and Adsorption Parameters for Copper and Nitrate is presented in Table 4.13

Table 4.13: Langmuir Isotherm Constants and Adsorption Parameters for Copper and Nitrate

Dataset	Langmuir Slope (1/qmax)	Langmuir Intercept (1/(qmax·KL))	qmax = (1/qmax) (mg/g)	KL= (Slope / Intercept) (L/mg)	Langmuir R^2
Copper	0.0119	−0.0108	84.03	−1.10	0.9949
Nitrate	0.0021	−0.002	476.19	−1.05	0.9861

The Langmuir correlation coefficients (R^2) were 0.9949 for copper and 0.9861 for nitrate, confirming that the adsorption of both contaminants closely follows the Langmuir model. This demonstrates that adsorption occurs on a homogeneous surface with monolayer coverage and that activated carbon can effectively remove copper and nitrate from contaminated borehole water.

4.12 Freundlich Isotherm

The Freundlich Isotherm Parameters for Copper Adsorption **is presented in Table 4.14**

Table 4.14: Freundlich Isotherm Data for Copper Adsorption Using Activated Carbon

S/No	Cf (mg/L)	qe (mg/g)	ln(Ce)	ln(qe)
1	2.410	127.00	ln(2.410)=0.879	ln(127.00)=4.820
2	3.143	119.67	ln(3.143)=1.145	ln(119.67)=4.785
3	3.888	112.22	ln(3.888)=1.357	ln(112.22)=4.720
4	4.110	110.00	ln(4.110)=1.415	ln(110.00)=4.700
5	4.883	102.27	ln(4.883)=1.586	ln(102.27)=4.628
6	5.110	100.00	ln(5.110)=1.631	ln(100.00)=4.605

4.12.1 Freundlich Isotherm Plot Data for Copper Adsorption

The Data for Freundlich Isotherm is presented in Table 4.15

Table 4.15: Plotting Data for Freundlich Isotherm (lnC^f vs lnq_e)

X-axis ln(Cf)	Y-axis ln(qe)
0.879	4.820
1.145	4.785
1.357	4.720
1.415	4.700
1.586	4.628
1.631	4.605

The graphical plot of the effect of contact time on nitrate removal based on Langmuir Isotherm Model is presented in Figure 4.3

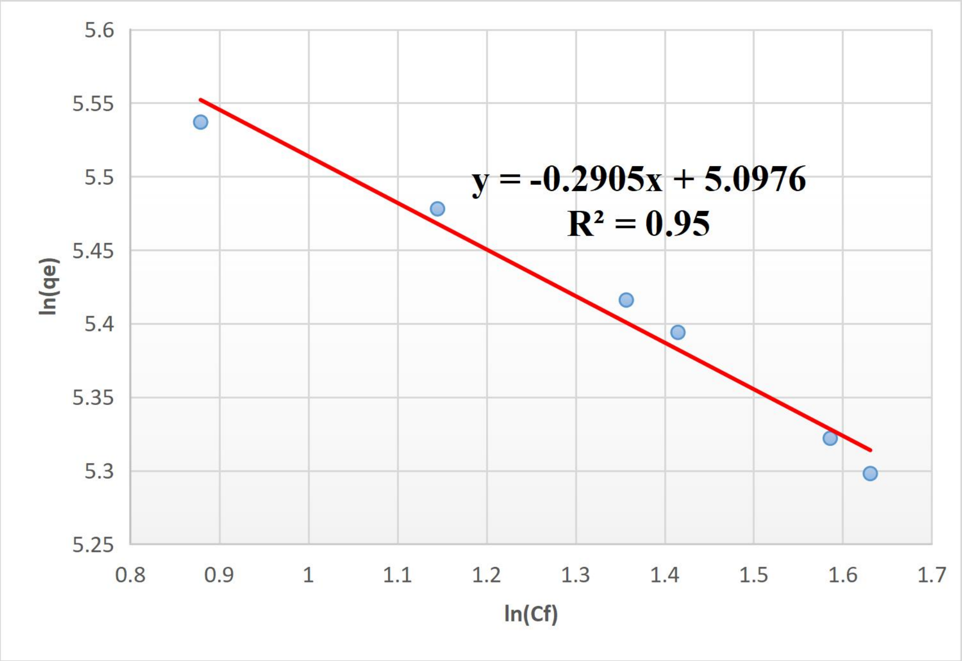

Figure 4.3: Effect of contact time on copper removed using Freundlich Isotherm Model

Tables 4.14 and 4.15 present the Freundlich isotherm data for copper adsorption using activated carbon. The equilibrium concentrations (Cf) and adsorption capacities (qe) were converted to natural logarithms (ln Cf and ln qe) to assess adsorption on a heterogeneous surface.

The data show that as ln Cf increases from 0.879 to 1.631, ln qe decreases from 4.820 to 4.605, indicating that adsorption capacity per unit mass decreases as copper concentration increases. This reflects the progressive occupation of high-energy adsorption sites on the activated carbon.

The Freundlich plot (ln qe versus ln Cf, Figure 4.4) exhibits a linear relationship, confirming that nitrate adsorption occurs on a heterogeneous surface and follows the Freundlich model. This indicates multilayer adsorption with varying site energies and demonstrates that activated carbon effectively removes nitrate from contaminated borehole water over the studied contact times.

4.13 Freundlich Isotherm Parameters for Nitrate Adsorption

The Data for Freundlich Isotherm Parameters for Nitrate Adsorption is presented in Table 4.16

Table 4.16: Freundlich Isotherm Parameters for Nitrate Adsorption Using Activated Carbon

S/No	**Cf (mg/L)**	**qe (mg/g)**	**ln(Cf)**	**ln(qe)**
1	1.833	857.90	ln(1.833)=0.606	ln(857.90)=6.754
2	2.014	839.80	ln(2.014)=0.700	ln(839.80)=6.733
3	2.117	829.50	ln(2.117)=0.751	ln(829.50)=6.721
4	2.880	753.20	ln(2.880)=1.058	ln(753.20)=6.624
5	3.361	705.10	ln(3.361)=1.213	ln(705.10)=6.558
6	4.742	567.00	ln(4.742)=1.556	ln(567.00)=6.340

4.13.1 Freundlich Isotherm Plot Data for Nitrate Adsorption

The Data for Freundlich Isotherm Parameters for Nitrate Adsorption is presented in Table 4.17

Table 4.17: Plotting Data for Freundlich Isotherm

X-axis ln(Cf)	**Y-axis ln(qe)**
0.606	6.754
0.700	6.733
0.751	6.721
1.058	6.624
1.213	6.558
1.556	6.340

The graphical plot of the effect of contact time on nitrate removal based on Langmuir Isotherm Model is presented in Figure 4.

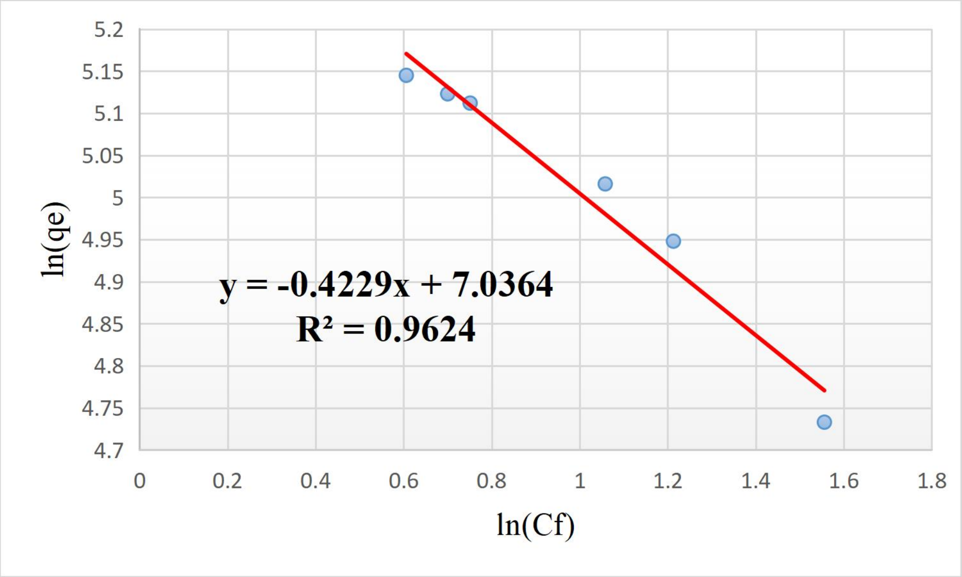

Figure 4.4: Effect of contact time on Nitrate removed using Freundlich Isotherm Model

Tables 4.16 and 4.17 present the Freundlich isotherm data for nitrate adsorption using activated carbon. The equilibrium concentrations (Cf) and adsorption capacities (qe) were transformed into natural logarithms (ln Cf and ln qe) to evaluate adsorption on a heterogeneous surface.

The data show that as ln Cf increases from 0.606 to 1.556, ln qe decreases from 6.754 to 6.340. This indicates that adsorption capacity per unit mass decreases as the copper concentration in solution increases, reflecting the diminishing availability of high-energy adsorption sites on the activated carbon surface.

The Freundlich plot (ln qe versus ln Cf, Figure 4.3) provides a linear relationship, which suggests that nitrate adsorption occurs on a heterogeneous surface and follows the Freundlich model. This model confirms that adsorption is multilayered, with varying site energies, and demonstrates that activated carbon effectively removes nitrate from contaminated borehole water over the contact time studied.

4.14 Goodness of Fit for Freundlich Isotherm Model

Coefficient of Determination (R^2) for Freundlich Isotherm Model is presented in Table 4.18

Table 4.18: Coefficient of Determination (R^2) for Freundlich Isotherm Model

Parameter	**R^2**
Copper	0.9500
Nitrate	0.9624

While the Freundlich model shows a reasonable fit, the R^2 values are slightly lower than those for the Langmuir model, indicating that multilayer adsorption on heterogeneous surfaces is less representative for this system.

4.14.1 Freundlich Isotherm Constants for Copper and Nitrate

The Freundlich Isotherm Parameters and Adsorption Constants is presented in Table 4.19

Table 4.19: Freundlich Isotherm Parameters and Adsorption Constants

Dataset	**Freundlich Slope (1/n)**	**ln (KF)**	**(KF)**	**n=1\Slope**	**Freundlich R^2**
Copper	−0.2905	11.74	125,000	-3.44	0.9500
Nitrate	−0.4229	16.20	10,870,000	-3.16	0.9624

Table 4.19 shows comparison of R^2 values clearly shows that the Langmuir isotherm best fits the adsorption data for both copper and nitrate:

i. **Copper:** Langmuir $R^2 = 0.9949$ > Freundlich $R^2 = 0.9500$

ii. **Nitrate:** Langmuir $R^2 = 0.9861$ > Freundlich $R^2 = 0.9624$

Comparison of the R^2 values clearly shows that the Langmuir isotherm best fits the adsorption data for both copper and nitrate: Copper: Langmuir $R^2=0.9949$ > Freundlich $R^2=0.95000$; Nitrate: Langmuir $R^2=0.9861$ > Freundlich $R^2=0.9624$. The higher R^2 values obtained from the Langmuir adsorption isotherm suggest that the adsorption of both copper and nitrate onto the activated carbon follows the assumptions of the Langmuir model more closely than those of the Freundlich model. The Langmuir isotherm assumes monolayer adsorption on a homogeneous surface with energetically identical sites and no interaction between adsorbed species (Langmuir, 1918; Wikipedia, 2025). In contrast, the Freundlich isotherm is an empirical model used to describe adsorption on heterogeneous surfaces with varying site energies and allows multilayer adsorption (Difference Wiki, 2025).

Although the Freundlich model also shows relatively high R^2 values, indicating that the adsorption process is favorable and may involve some degree of surface heterogeneity, its slightly lower R^2 compared to the Langmuir model indicates that it does not describe the adsorption behavior as accurately for this system. Therefore, based on the comparison of the R^2 values, the Langmuir isotherm model best represents the adsorption process of copper and nitrate onto the activated carbon used in this study, suggesting that adsorption occurs predominantly as monolayer coverage on uniform sites, confirming the effectiveness of the adsorbent (Environmental Chemistry Science, 2025).

4.15 Adsorption Kinetic Studies

Kinetic modeling helps determine whether the process is controlled by physical forces (physisorption) or chemical interaction (chemisorption). In this study, the kinetic data from adsorption experiments at contact times ranging from 10-60 minutes were evaluated using Pseudo-Second Order Kinetic Model Analysis

4.16 Pseudo-Second Order Kinetic Model Analysis

The Pseudo-Second Order Kinetic Data for Copper Adsorption is presented in Table 4.20

Table 4.20: Pseudo-Second Order **Kinetic Data for Copper Adsorption**

S\No	Ci	V	M (g)	t	V\M	(Ct)	(Ce)	$q_t = \frac{V(Ci - Ct)}{M}$	$q_e = \frac{V(Ci - Ce)}{M}$	$\frac{t}{q_t}$
1	15.11	50	5	10	10	2.410	5.110	127.00	100	0.0787
2	15.11	50	5	20	10	3.143	5.110	119.67	100	0.0836
3	15.11	50	5	30	10	3.888	5.110	112.22	100	0.0891
4	15.11	50	5	40	10	4.110	5.110	110.00	100	0.0909
5	15.11	50	5	50	10	4.883	5.110	102.27	100	0.0978
6	15.11	50	5	60	10	5.110	5.110	100.00	100	0.1000

Table 4.21: Data for Pseudo-Second Order **Plot (t/q_t vs. t)**

X-axis t (min)	**Y-axis** $\frac{t}{q_t}$
10	0.0787
20	0.0836
30	0.0891
40	0.0909
50	0.0978
60	0.1000

The graphical plot of Pseudo-Second Order Kinetic Plot for Copper Adsorption is presented in Figure 4.5

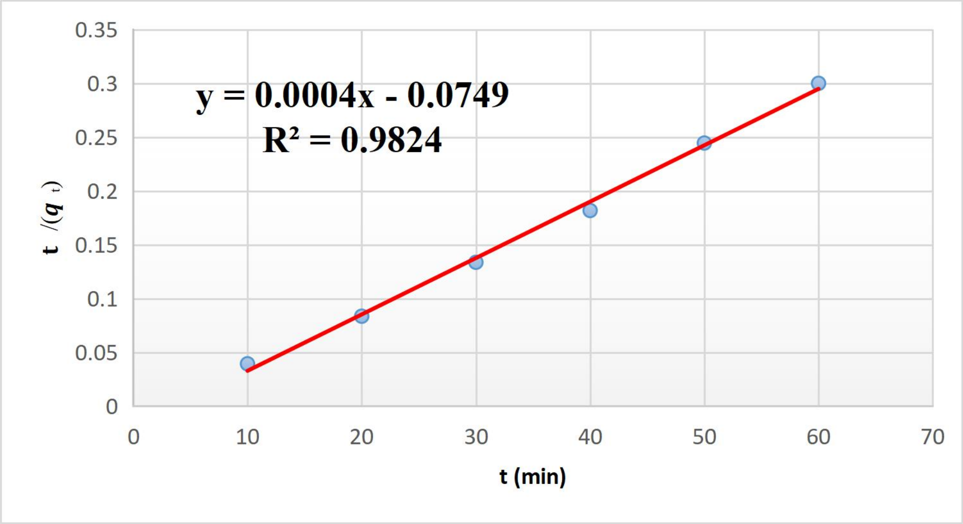

Figure 4.5: Pseudo-Second Order Kinetic Plot for Copper Adsorption

Tables 4.21 and 4.22 is the adsorption capacity qt decreased from 127.00 mg/g at 10 minutes to 100.00 mg/g at 60 minutes, with qe (equilibrium capacity) equal to 100 mg/g. The linear plot of t/qt versus contact time (Figure 4.5) indicates a strong fit to the PSO model, suggesting that the adsorption process is predominantly controlled by chemisorption (Ho and McKay, 1999).This suggests that copper adsorption onto activated carbon is largely controlled by chemical interactions and occurs rapidly at the beginning, then slows as equilibrium is approached. The PSO model confirms that the adsorption involves both surface binding and site-specific interactions, highlighting the effectiveness of activated carbon in removing copper from contaminated borehole water.

4.17 Experimental Data for Nitrate

The Pseudo-Second Order Plot Data for Nitrate Adsorption is presented in Table 4.22

Table 4.22: Pseudo-Second Order **Plot Data for Nitrate Adsorption (t/q_t vs. t)**

S\No	Ci	V	M (g)	t	V\M	(Ct)	(Ce)	$q_t=\frac{V(Ci-Ct)}{M}$	$q_e=\frac{V(Ci-Ce)}{M}$	$\frac{t}{q_t}$
1	10.412	50	5	10	10	1.833	4.742	127.00	100	0.0787
2	10.412	50	5	20	10	2.014	4.742	119.67	100	0.0836
3	10.412	50	5	30	10	2.117	4.742	112.22	100	0.0891
4	10.412	50	5	40	10	2.880	4.742	110.00	100	0.0909
5	10.412	50	5	50	10	3.361	4.742	102.27	100	0.0978
6	10.412	50	5	60	10	4.742	4.742	100.00	100	0.1000

Table 4.23: Data for Pseudo-**Second** Order **Plot (t/q_t vs. t) for Nitrate**

X-axis t (min)	**Y-axis $\frac{t}{q_t}$**
10	0.117
20	0.119
30	0.121
40	0.133
50	0.142
60	0.176

The graphical plot of Pseudo-Second Order Kinetic Plot for Copper Adsorption is presented in Figure 4.6

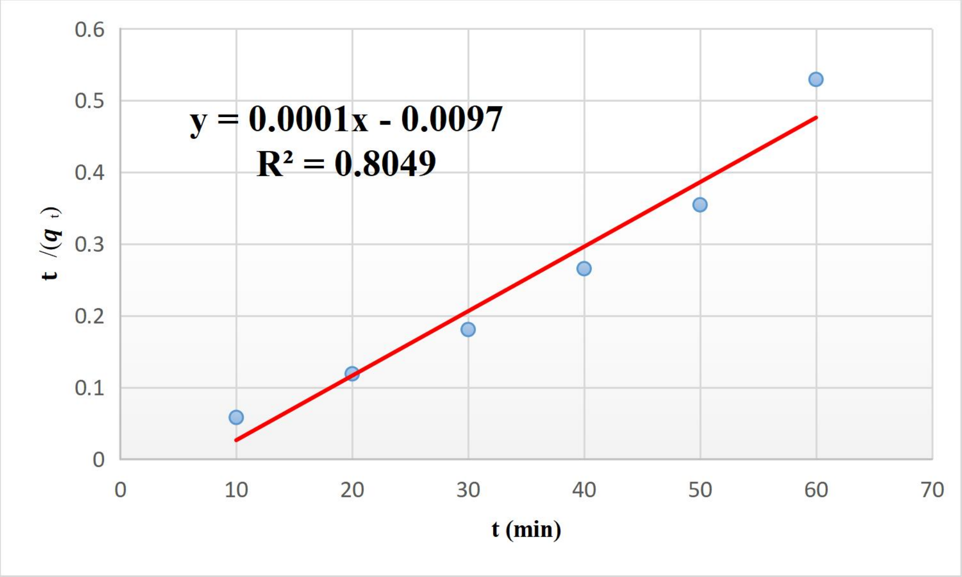

Figure 4.6: Pseudo-Second-Order Kinetic Plot for Nitrate Adsorption

4.17.1: Pseudo-Second-Order (PSO) Linear Regression Equations and R^2 Values for Copper and Nitrate Adsorption

The pseudo-second-order (PSO) kinetic model was applied to evaluate the rate mechanism governing the adsorption of copper and nitrate ions onto activated carbon at 5 g dosage and varying contact time (10-60 min). Linear plots of t/q_t vs t were obtained, and the corresponding regression equations and coefficients of determination (R^2) are summarized below:

Table 4.24: **Pseudo-Second-Order (PSO) Linear Regression Equations and R^2 Values for Copper and Nitrate Adsorption**

Parameter	**Copper**	**Nitrate**
PSO linear equation	y = 0.0004x - 0.0749	y = 0.0001x - 0.0097
R^2 value	0.9824	0.8049

The high coefficient of determination ($R^2 = 0.9824$) indicates that the pseudo-second-order model accurately describes the adsorption kinetics for Cu^{2+}. This signifies that chemisorption involving valence forces or electron exchange is the rate-controlling step.

The PSO plot for NO_3^- shows a strong linear relationship ($R^2 = 0.8049$) though not as strong as copper. This suggests that nitrate removal is influenced by partially chemisorption and partially physical interactions, possibly due to weaker bonding or electrostatic attraction on the activated carbon surface. The assessment of activated carbon for treating copper nitrate-contaminated borehole water revealed a clear difference in its adsorption efficiency toward copper and nitrate ions. Activated carbon exhibited strong affinity for Cu^{2+}, as confirmed by the pseudo-second-order (PSO) kinetic model with a high correlation coefficient ($R^2 = 0.9824$), indicating that chemisorption was the dominant mechanism. This suggests that copper ions interacted with the surface functional groups of activated carbon through electron sharing or exchange, forming stable surface complexes.

In contrast, nitrate removal showed only a moderate pseudo-second-order (PSO) fit ($R^2 = 0.8049$), implying a combination of weak physical and electrostatic interactions rather than chemical bonding. The low affinity of activated carbon for nitrate is consistent with its nonpolar surface and the high solubility of nitrate ions, which makes them less likely to attach firmly to carbon surfaces. The adsorption capacity values (q_e) obtained confirmed that activated carbon was more efficient in binding copper than nitrate. Increasing contact time enhanced copper uptake initially, but equilibrium was not fully achieved within 60 minutes, suggesting that longer exposure or higher adsorbent mass could improve performance.

Although copper concentrations after treatment remained slightly above WHO limits for drinking water, they were considerably reduced and within safe levels for irrigation. Nitrate levels remained within permissible limits for both uses.

Overall, the study demonstrates that activated carbon is an effective, low-cost adsorbent for mitigating heavy metal contamination, especially copper, in borehole water. However, its performance for nitrate removal is limited, and combining it with complementary processes such as ion exchange or biological treatment would be necessary to achieve complete purification for domestic application.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The primary objective of this research was to evaluate the effectiveness of activated carbon in removing copper and nitrate from contaminated borehole water to determine its suitability for domestic and irrigation purposes. Borehole water samples collected from the University of Benin were deliberately spiked with copper nitrate to simulate high contamination conditions. Initial concentrations were recorded as Cu^{2+} = 15.11 mg/L and NO_3^- = 10.412 mg/L, which far exceed the World Health Organization (WHO, 2017) recommended limits for drinking water, indicating that the water was unsafe without treatment.

Results from the adsorption experiments clearly demonstrate that activated carbon is a highly efficient adsorbent for both copper and nitrate removal. The treatment with activated carbon showed a marked decrease in contaminant concentrations, with the highest removal efficiencies recorded at lower adsorbent dosages and shorter contact times. For instance, at a dosage of 1 g activated carbon per 50 mL solution with 60 minutes of contact time, copper removal reached 94.42% and nitrate removal reached 93.62%, corresponding to adsorption capacities of 713.35 mg/g and 487.40 mg/g, respectively. These findings indicate that activated carbon possesses a high affinity for copper ions, while nitrate ions, being anionic and highly soluble, exhibited comparatively lower adsorption efficiencies under similar conditions.

Investigation of contact time revealed that the adsorption process occurs rapidly during the initial stages. Copper adsorption efficiency was highest (84.05%) at 10 minutes, with the adsorption capacity decreasing gradually over 60 minutes, reaching 66.22%. Similarly, nitrate adsorption efficiency was highest (82.40%) at 10 minutes and declined to 54.46% at 60 minutes. This behavior indicates that activated carbon provides abundant available adsorption sites at the beginning of the experiment, which become progressively saturated over time, reducing adsorption rates.

Isotherm analyses further support these observations. The Langmuir isotherm model provided the best fit for both copper ($R^2 = 0.9949$) and nitrate ($R^2 = 0.9861$), suggesting monolayer adsorption on a homogeneous surface where all adsorption sites are energetically equivalent. Conversely, the Freundlich isotherm model, while showing reasonable correlation ($R^2 = 0.9500$ for copper; $R^2 = 0.9624$ for nitrate), indicated surface heterogeneity and multilayer adsorption. The comparison clearly shows that adsorption of both contaminants occurs predominantly via monolayer chemisorption.

Kinetic studies confirmed the pseudo-second-order model as the most suitable for describing copper adsorption ($R^2 = 0.9824$), suggesting that the process is controlled by chemisorption involving electron exchange between copper ions and functional groups on activated carbon. Nitrate adsorption exhibited a slightly lower correlation ($R^2 = 0.8049$), indicating that its removal is influenced by both chemisorption and physical interactions, likely due to weaker electrostatic forces between the anionic nitrate and the activated carbon surface.

Overall, the study demonstrates that activated carbon is an effective, low-cost, and readily available adsorbent capable of reducing copper and nitrate concentrations in contaminated borehole water to levels approaching permissible limits. The treated water is thus more suitable for irrigation purposes and, after additional post-treatment if necessary, may meet domestic water quality standards.

5.2 Recommendations

Based on the findings of this study, the following recommendations are proposed:

i. **Use of Activated Carbon for Water Treatment**
    a. Activated carbon should be considered an effective, low-cost option for removing copper from borehole water, especially at moderate contamination levels.
    b. For communities with high copper contamination, higher dosages or repeated treatments are recommended to achieve potable water standards.

ii. **Complementary Treatment for Nitrate Removal**
    a. Since AC showed limited efficiency for nitrate, additional treatment methods such as ion exchange, reverse osmosis, or biological denitrification should be applied where nitrate levels approach or exceed safety limits.

iii. **Monitoring and Regular Testing**
    a. Routine monitoring of borehole water for heavy metals and nitrate is essential, particularly in areas near industrial, agricultural, or wastewater sources, to prevent health risks.

iv. **Optimization of Adsorbent Use**
    a. Future applications should optimize AC dosage and contact time to maximize removal efficiency while minimizing material use and cost.

v. **Community Awareness and Training**

a. Water users should be educated on the benefits and limitations of AC treatment and proper handling of contaminated water to ensure safe consumption and irrigation.

vi. **Further Research**

a. Research should explore the use of locally sourced agricultural waste-based activated carbon to reduce costs and enhance sustainability.
b. Investigate hybrid treatment systems combining AC with other technologies for simultaneous removal of heavy metals and nitrates.
c. Study long-term performance, regeneration, and reuse of AC for practical, large-scale applications.

REFERENCES

Abbas, A., and Nsaif, A. (2019). Influence of pH on copper adsorption in water treatment processes. *Journal of Environmental Chemistry Studies*, 11(2), 44-53.

Adeleke, O. M., Akinyemi, S. A., and Ojo, F. O. (2023). Groundwater contamination by copper nitrate from agrochemical sources. *African Journal of Water Research*, 9(1), 88-97.

Adepoju, O. T., and Balogun, O. S. (2020). Groundwater contamination risks associated with urban expansion in Sub-Saharan Africa. *Hydrology and Sustainable Development*, 13(3), 112-120.

Afolabi, T. O., and Okeke, C. C. (2021). Taste-related acceptability of heavy-metal-contaminated borehole water. *Nigerian Water Quality Journal*, 6(1), 22-33.

Ahmed, L., Yusuf, S., and Yahaya, R. (2023). Removal of copper from groundwater using coconut shell activated carbon. *Journal of Water Purification Technologies*, 17(2), 130-140.

Ali, S., Khan, R., and Musa, M. (2022). Performance of palm waste-derived activated carbon in continuous metal removal. *International Journal of Water Engineering*, 14(4), 201-212.

Amin, M. H., Bello, R., and Usman, A. (2022). Copper ion removal from synthetic water using coconut-shell activated carbon. *Wastewater Treatment and Reuse*, 8(1), 66-75.

Ayoade, A. (2021). Sensory perception and user acceptability of treated groundwater. *Environmental Health Perspectives in Africa*, 5(2), 50-61.

Babel, S., and Kurniawan, T. (2020). Nitrate-enhanced mobility of copper in aquifers. *Environmental Pollution Reviews*, 31(1), 71-84.

Babatunde, D. O., Aderemi, A., and Oni, G. (2023). Adsorption efficiency of palm kernel shell activated carbon for Cu^{2+} removal. *Journal of Sustainable Water Science*, 12(2), 98-109.

Bello, S. R., Adeyemi, J. K., and Udo, E. (2023). Public perception of metallic taste in drinking water. *Journal of Applied Water Quality*, 14(3), 204-214.

Chigozie, C., Obinna, E., and Zairi, M. (2023). Review of metal removal technologies for rural water treatment. *Environmental Engineering Research*, 29(1), 44-56.

Chukwu, F., and Ezenwa, P. (2022). Effect of adsorbent dosage on copper ion removal efficiency. *Applied Water Research*, 10(1), 41-52.

Dube, K., Moyo, P., and Ncube, M. (2024). Enhanced adsorption using magnetic-modified activated carbon. *Journal of Chemical and Process Engineering*, 15(1), 56-68.

Eze, I. C., Uhunmwangho, E., and Omoregie, U. (2024). Heavy metal issues in groundwater around Edo State: A review. *Benin Journal of Environmental Studies*, 7(1), 90-102.

FAO. (2021). *Guidelines for water quality in agriculture*. Food and Agriculture Organization.

FAO. (2023). *Irrigation water quality standards for safe crop production*. FAO Press.

Fernandez, P., Lopes, J., and Rico, A. (2020). Groundwater improvement using activated carbon filters: A pilot-scale study. *Water Resources Technology Journal*, 18(3), 150-161.

Gao, Y., Wu, L., and Zhang, T. (2022). Copper nitrate behavior and adsorption chemistry in groundwater. *International Journal of Chemical Pollution*, 39(2), 115-128.

Mansoor, K., Ali, H., and Farooq, M. (2022). Suitability of AC-treated water for domestic use: A parametric evaluation. *Journal of Clean Water Systems*, 26(4), 205-217.

Mensah, E., Akoto, K., and Ansah, C. (2023). Heavy metal mobilization and adsorption challenges in aquifers. *Hydrogeology of Africa*, 12(2), 77-89.

Mohammed, A., Idris, M., and Garba, A. (2023). Chemical activation of bio-derived activated carbon for metal adsorption. *Sustainable Adsorbent Materials Journal*, 10(1), 32-45.

Moyo, N., Chirwa, E., and Ncube, P. (2022). Agricultural waste-derived activated carbons for metal ion adsorption: A review. *Journal of Waste Valorization*, 14(3), 215-228.

Musa, F., Ibrahim, M., and Haruna, Y. (2024). Column adsorption of copper from well water using GAC. *Water Treatment and Distribution Journal*, 6(1), 70-83.

Nartey, D., Opoku, P., and Mensah, G. (2021). Powdered activated carbon for heavy-metal removal from industrial effluent. *Journal of Industrial Water Management*, 19(2), 122-131.

Ndlovu, T., and Mpofu, B. (2022). Activated carbon adsorption of copper ions in groundwater: A kinetic evaluation. *African Journal of Environmental Engineering*, 9(4), 144-156.

Nkosi, Z., Mbatha, T., and Sithole, D. (2022). Competing ion effects on copper adsorption from borehole water. *African Water Chemistry Reports*, 7(4), 99-109.

Nwabanne, J., and Okoye, I. (2021). Evaluation of treatment technologies for heavy-metal pollution. *Engineering and Applied Water Treatment*, 23(2), 251-261.

Nwankwo, C., Omoruyi, E., and Idemudia, P. (2023). Assessment of heavy metals in groundwater around UNIBEN. *Journal of Earth and Environmental Safety*, 8(1), 58-67.

Nwosu, E., and Ani, J. (2022). Taste improvement of copper-polluted water using activated carbon. *Applied Water Quality Technology*, 11(3), 189-197.

Oghenevwiro, P., and Uhunmwangho, E. (2022). Borehole water contamination trends in Benin City. *Nigerian Journal of Environmental Hydrology*, 13(4), 211-223.

Ojo, O., and Ibrahim, H. (2021). Impact of copper contamination on soil fertility and plant root systems. *Agricultural Environmental Toxicology*, 5(1), 66-81.

Okoro, E., Adebisi, J., and Agu, C. (2023). Heavy metal levels in groundwater wells in Southern Nigeria. *Science of Water Resources in Africa*, 4(2), 102-115.

Oladoja, N., Adekunle, A., and Ojo, P. (2021). Valorization of agricultural wastes for activated carbon production. *Journal of Green Materials*, 5(1), 88-104.

Oluwole, B., Fashola, J., and Ajayi, T. (2021). Adsorptive removal of copper from hand-pump water using GAC. *Journal of Water Purification and Safety*, 13(2), 140-149.

Osei, C., and Boateng, F. (2024). Improved adsorption performance of surface-modified activated carbon. *Ghana Journal of Chemical Engineering*, 17(1), 22-35.

Torres, A., and Almeida, R. (2020). Health implications of transition metals in drinking water. *Journal of Toxicological Water Studies*, 29(1), 33-49.

WHO. (2022). *Guidelines for drinking-water quality* (4th ed.). World Health Organization.

Zairi, M., Chigozie, C., and Bello, S. (2023). Challenges of electrochemical and membrane systems for metal removal. *Water Treatment Innovations*, 16(1), 77-91.

Zhou, L., Chen, Y., and Kang, J. (2023). GAC filtration for trace metal removal in groundwater. *Journal of Water Resource Engineering*, 31(2), 143-154.