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DEVELOPMENT OF ACTIVATED CARBON FROM AGRICULTURAL WASTE, MAIZE COBS AND GROUNDNUTS SHELLS FOR WATER PURIFICATION

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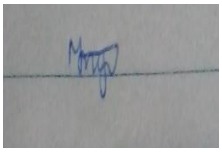
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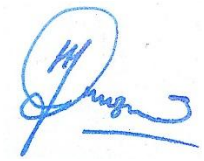
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ABSTRACT

Access to safe and clean water remains a major challenge in many developing countries, including Zimbabwe, where rural and peri-urban communities often depend on boreholes, wells, rivers, and dams that may be contaminated by agricultural runoff, poor sanitation, mining activities, and waste disposal. Although commercial activated carbon is widely used for water treatment because of its high adsorption capacity, its cost and dependence on imported or industrial raw materials limit its use among low-income communities. This study focuses on the development of low-cost activated carbon from locally available agricultural wastes, specifically maize cobs and groundnut shells, for water purification. The research aims to produce activated carbon through carbonization and activation processes, determine its physical and chemical properties, and evaluate its effectiveness in improving selected water quality parameters such as turbidity, pH, colour, and contaminant removal. The study will also compare the purification performance of maize cob-based activated carbon and groundnut shell-based activated carbon in order to recommend the most suitable material for affordable water treatment. By converting agricultural residues into useful adsorbents, the study promotes sustainable waste management, environmental protection, and community-level access to cleaner water. The findings are expected to contribute to the development of locally sourced, low-cost, and environmentally friendly water purification technologies for Zimbabwean communities.

Keywords: activated carbon, maize cobs, groundnut shells, water purification, agricultural waste, adsorption, Zimbabwe.

CHAPTER 1: INTRODUCTION

1.1 Introduction

Access to safe and clean water is a fundamental human right and an essential requirement for life, public health, agriculture, and industrial development. Despite global progress in water supply systems, many developing countries continue to face serious challenges related to water contamination and inadequate purification technologies. Unsafe water sources often contain suspended solids, microorganisms, heavy metals, pesticides, dyes, and other organic pollutants that threaten human health and environmental sustainability. According to the World Health Organization, contaminated water contributes significantly to waterborne diseases, particularly in low-income communities where treatment infrastructure is limited (WHO, 2022).

In Zimbabwe, many households, especially in rural and peri-urban areas, rely on boreholes, wells, rivers, and dams for domestic water supply. These sources are increasingly exposed to contamination from agricultural runoff, poor sanitation systems, mining activities, and waste disposal practices. As a result, there is growing demand for affordable and locally available water purification technologies that can improve water quality without high operational costs. Conventional treatment methods such as membrane filtration, reverse osmosis, and chemical dosing are effective but often expensive and technically demanding for small communities (UNICEF, 2021).

Activated carbon is one of the most widely used adsorbent materials in water treatment because of its large surface area, well-developed pore structure, and strong adsorption capacity. It is capable of removing colour, odour, dissolved organics, chlorine residues, and certain toxic metals from water. However, commercial activated carbon is often expensive because it is manufactured from coal or industrial-grade raw materials using energy-intensive processes. This cost limits its accessibility in developing nations where affordable alternatives are urgently needed (Tan et al., 2020).

Recent studies have shown that agricultural wastes can be converted into effective activated carbon for water purification. Biomass materials such as coconut shells, rice husks, banana peels, maize cobs, and nut shells contain lignocellulosic compounds rich in carbon, making them suitable precursors for activated carbon production. Through carbonization and activation processes, these

materials can be transformed into porous adsorbents with significant pollutant removal capabilities (Mohan et al., 2019). Zimbabwe produces large quantities of maize and groundnuts annually, generating maize cobs and groundnut shells as agricultural residues. These materials are often discarded through open burning or dumping, causing environmental pollution and waste of potentially valuable resources.

This study therefore focuses on the development of activated carbon from maize cobs and groundnut shells for water purification. By utilizing locally available agricultural waste, the research seeks to provide a sustainable, low-cost, and environmentally friendly solution to water treatment challenges.

1.2 Background of the Study

The global demand for clean water continues to rise due to population growth, industrialization, urbanization, and climate change. At the same time, freshwater resources are under pressure from pollution caused by industrial discharge, agricultural chemicals, sewage effluent, and mining waste. Many communities lack access to centralized water treatment systems, making household and community-level purification technologies increasingly important (United Nations, 2023).

Adsorption has become one of the most preferred water treatment methods because it is simple, efficient, and relatively low-cost. Activated carbon is the most common adsorbent used worldwide because it can remove a wide range of contaminants from water. It functions through physical adsorption and chemical interactions between pollutants and the porous carbon surface (Li et al., 2021).

However, the cost of imported commercial activated carbon remains a challenge in many African countries. This has encouraged research into locally sourced alternatives derived from agricultural residues. Studies have demonstrated successful activated carbon production from biomass wastes, with adsorption performance comparable to some commercial products (Kumar et al., 2020).

Zimbabwe is an agricultural economy with maize being the staple crop and groundnuts widely cultivated in many provinces. Consequently, maize cobs and groundnut shells are available in significant quantities. If converted into activated carbon, these wastes can help solve two major problems simultaneously: waste management and water purification.

1.3 Problem Statement

Many communities in Zimbabwe face difficulties in accessing affordable and efficient water purification systems. Commercial activated carbon filters are expensive and often imported, making them unaffordable for low-income households, schools, clinics, and rural communities.

At the same time, maize cobs and groundnut shells are produced in large quantities as agricultural waste and are frequently disposed of through burning or dumping, which contributes to environmental pollution.

Although agricultural biomass has shown potential for activated carbon production in many countries, limited local studies have specifically investigated the production of activated carbon from maize cobs and groundnut shells for water purification in Zimbabwe. Therefore, there is a need to develop and evaluate low-cost activated carbon from these agricultural residues.

1.4 Aim of the Study

To develop activated carbon from maize cobs and groundnut shells and evaluate its effectiveness for water purification.

1.5 Research Objectives

1. To produce activated carbon from maize cobs and groundnut shells using carbonization and activation methods.
2. To determine the physical and chemical properties of the produced activated carbon.
3. To assess the effectiveness of the activated carbon in removing contaminants from water.
4. To compare the purification performance of maize cob activated carbon and groundnut shell activated carbon.
5. To recommend the most suitable agricultural waste material for low-cost water purification.

1.6 Research Questions

1. Can maize cobs and groundnut shells be converted into quality activated carbon?
2. What are the physical and chemical characteristics of the produced activated carbon?

3. How effective is the activated carbon in purifying contaminated water?
4. Which raw material produces better activated carbon for water treatment?
5. Can locally produced activated carbon provide an affordable alternative to commercial products?

1.7 Significance of the Study

This study is important because it promotes sustainable use of agricultural waste materials for environmental and economic benefit. Converting maize cobs and groundnut shells into activated carbon reduces waste disposal problems and adds value to local biomass resources.

The research will benefit communities by providing an affordable option for water purification, especially in rural and low-income areas. It may also support entrepreneurs interested in small-scale activated carbon production. Furthermore, the study contributes to scientific knowledge on biomass-based adsorbents and sustainable water treatment technologies.

1.8 Scope of the Study

The study will focus on maize cobs and groundnut shells as raw materials for activated carbon production. The work will include raw material preparation, carbonization, chemical activation, washing, drying, and characterization.

Water purification experiments will evaluate parameters such as turbidity, pH, colour reduction, and selected contaminant removal efficiency under laboratory conditions.

1.9 Limitations of the Study

The study may be limited by access to advanced laboratory equipment for detailed characterization such as BET surface area analysis and scanning electron microscopy. Financial constraints may also limit the number of experiments conducted.

Additionally, the research will focus on selected water quality parameters and may not test every possible contaminant found in natural water sources.

1.10 Definition of Key Terms

Activated Carbon: A porous carbon material with high adsorption capacity used for purification.

Adsorption: The process by which molecules attach to the surface of a solid material.

Carbonization: Heating biomass in the absence of oxygen to produce char.

Activation: Treatment of char to increase pore structure and surface area.

Agricultural Waste: Residues left after harvesting or processing crops.

1.11 Chapter Summary

This chapter introduced the study on developing activated carbon from maize cobs and groundnut shells for water purification. It outlined the background, problem statement, aim, objectives, research questions, significance, scope, and limitations of the study. The next chapter reviews related literature on activated carbon production, adsorption mechanisms, biomass precursors, and previous studies in water treatment.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews literature related to the production of activated carbon from agricultural waste materials and its application in water purification. The review examines theoretical perspectives, empirical studies, and recent technological developments concerning water pollution, water treatment technologies, adsorption processes, activated carbon production, and the utilisation of agricultural residues such as maize cobs and groundnut shells as precursor materials. The chapter further discusses the theoretical framework underpinning the study, reviews previous studies on similar materials, identifies existing knowledge gaps, and establishes the basis upon which the current research is founded.

A literature review is an indispensable component of scientific research because it provides a critical examination of existing knowledge and helps identify areas requiring further investigation. Snyder (2019) distinguishes between integrative, systematic, and semi-systematic review approaches, emphasising that each serves to map accumulated findings and illuminate research frontiers. In the context of environmental and water treatment research, reviews assist scholars in understanding current technologies, methodological choices, and opportunities for sustainable innovation. The present review is particularly important because it demonstrates the potential of converting agricultural waste into value-added adsorbents capable of improving water quality while simultaneously addressing waste management challenges in developing country contexts.

2.2 Global Water Pollution Challenges

Water is among the most critical natural resources sustaining human life, agriculture, industry, and economic development. Despite its indispensability, access to clean and safe drinking water remains a profound global challenge. According to the World Health Organization (WHO, 2022), approximately 1.7 billion people worldwide use a drinking water source contaminated with faecal matter, substantially elevating the risk of waterborne disease transmission. The United Nations Environment Programme (UNEP, 2021) further reports that approximately 80 percent of all wastewater generated globally is discharged into the environment without prior treatment, exerting severe pressure on freshwater ecosystems.

Industrial activities rank among the principal contributors to water pollution worldwide. Manufacturing, mining, and processing industries frequently discharge inadequately treated

effluents containing heavy metals, synthetic dyes, acids, and toxic organic compounds into rivers, lakes, and groundwater systems. Vardhan et al. (2019) established that heavy metals such as lead, mercury, cadmium, and arsenic are particularly hazardous because they are non-biodegradable, tend to bioaccumulate within living organisms, and produce severe neurological, renal, and carcinogenic consequences at chronic exposure levels. A comprehensive review by Chowdhury et al. (2022) confirmed that industrial effluents represent the dominant pathway through which heavy metals enter freshwater systems in developing nations, where regulatory enforcement and treatment infrastructure remain inadequate.

Agricultural activities contribute substantially to water contamination through the leaching and runoff of fertilisers, pesticides, and herbicides into rivers and groundwater during rainfall events. Eutrophication arising from excessive nutrient loading is a well-documented consequence, resulting in oxygen depletion, proliferation of harmful algal blooms, and deterioration of aquatic biodiversity (Ahmed et al., 2021). Pesticide residues similarly pose risks to both human populations consuming contaminated water and to non-target aquatic species. Climate change compounds these challenges by altering hydrological cycles, intensifying droughts that concentrate pollutants in reduced water volumes, and generating flood events that mobilise contaminants from agricultural fields and industrial sites into receiving water bodies (IPCC, 2022).

The public health consequences of water pollution are devastating. Contaminated water serves as a principal transmission route for cholera, typhoid, dysentery, hepatitis A, and diarrhoeal diseases. Prüss-Üstün et al. (2019) estimated that approximately 829 000 deaths occur annually from diarrhoeal disease attributable to unsafe water, sanitation, and hygiene, with the burden disproportionately concentrated in low-income nations. These epidemiological realities reinforce the urgent need for affordable, locally appropriate, and technically robust water treatment technologies capable of serving growing populations in resource-constrained environments.

2.3 Water Pollution in Zimbabwe

Zimbabwe faces substantial water quality and accessibility challenges arising from the convergence of rapid urbanisation, extensive mining activity, agricultural intensification, and severely constrained public investment in water infrastructure. Although the country is endowed with numerous perennial rivers, dams, and groundwater resources, many communities cannot reliably access safe drinking water.

Urban centres, including Harare, Bulawayo, Mutare, and Gweru, have experienced prolonged pressure on aging sewage and water supply infrastructure. Frequent sewage overflows, burst pipelines, and under-resourced treatment works have resulted in documented contamination of urban water sources. Nhapi (2022) examined wastewater management challenges in Zimbabwean cities and found that most treatment facilities were operating below design capacity and discharging only partially treated effluents into rivers, thereby degrading downstream water quality. The Harare Water Supply catchment area, comprising the Manyame River system, has experienced consistent deterioration in water quality indicators associated with urbanisation and infrastructure neglect.

Mining activity constitutes another major source of water contamination in Zimbabwe, a country with significant operations spanning gold, platinum, chrome, coal, and diamond extraction. Acid mine drainage, tailings seepage, and process effluents release heavy metals and acidic compounds into adjacent watercourses and groundwater systems. Meck et al. (2021) reported elevated concentrations of cadmium, lead, zinc, and arsenic in rivers surrounding artisanal gold mining areas in Mashonaland West, with levels exceeding WHO drinking water guidelines and posing acute risks to communities relying on these water bodies.

Agricultural runoff during the rainy season transports agrochemicals, nitrates, and phosphates into rivers and reservoirs, contributing to eutrophication and chemical contamination of rural water supplies. Communities in regions without piped water infrastructure rely heavily on boreholes, shallow wells, and open surface water sources that are frequently susceptible to microbiological and chemical contamination (Magidi and Ahmed, 2019). The convergence of these pollution sources with inadequate treatment capacity creates strong impetus for developing low-cost, locally producible water treatment materials that can function effectively under Zimbabwean conditions. The production of activated carbon from agricultural residues such as maize cobs and groundnut shells represents precisely the kind of context-appropriate solution that addresses both water quality and agricultural waste management simultaneously.

2.4 Water Purification Technologies

Water purification encompasses the removal of physical, chemical, and biological contaminants to render water safe for drinking and domestic use. Multiple technologies have been developed to

address the broad range of contaminants present in natural and impacted water sources, each with characteristic performance envelopes, cost profiles, and operational requirements.

Sedimentation and coagulation-flocculation processes are among the most widely applied preliminary treatment steps. Coagulants such as aluminium sulphate cause destabilisation and aggregation of colloidal particles, facilitating their removal by gravity settling. While these processes effectively reduce turbidity and suspended solids, they provide limited removal of dissolved contaminants, heavy metals, or micropollutants. Sand filtration, widely deployed in community water supply schemes, extends particulate removal but similarly offers limited capacity against dissolved organic compounds and trace metals (Simate et al., 2022).

Chemical disinfection, primarily chlorination, remains the most common method for inactivating microbial pathogens in treated water. Despite its effectiveness and cost-efficiency at scale, chlorination generates disinfection by-products including trihalomethanes and haloacetic acids that pose carcinogenic risks at elevated concentrations. Advanced oxidation processes and ultraviolet disinfection offer alternatives with fewer by-product concerns but require substantially greater capital investment and operational sophistication (Okoye-Chine et al., 2021).

Membrane-based processes, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, achieve exceptionally high contaminant rejection rates, including dissolved salts, heavy metals, and microorganisms. Reverse osmosis systems, in particular, are capable of producing water meeting the highest quality standards; however, their capital, energy, and maintenance requirements severely limit applicability in rural and peri-urban communities in developing countries. These barriers have motivated sustained research interest in adsorption-based treatment as a simpler, lower-cost alternative (Ighalo et al., 2022).

Adsorption technology has emerged as one of the most promising approaches for water purification in resource-limited settings due to its simplicity, operational flexibility, and capacity to remove a diverse range of pollutants. Adsorption involves the mass transfer of contaminants from solution onto the surface of a solid adsorbent. Activated carbon is the most widely applied adsorbent in both industrial and point-of-use treatment systems, owing to its exceptionally high surface area, tunable pore structure, and strong affinity for organic, inorganic, and metallic contaminants (Rathi and Kumar, 2021). The growing research focus on biomass-derived activated

carbon stems from its potential to provide sustainable and economically viable water treatment for communities that cannot access conventional infrastructure.

2.5 Activated Carbon: Properties and Classification

Activated carbon is a highly porous carbonaceous material characterised by an exceptionally developed internal surface area, a hierarchical network of micro-, meso-, and macropores, and a chemical surface bearing functional groups that confer adsorptive affinity for a wide range of contaminants. The material is produced through controlled thermal treatment of carbon-rich precursors under conditions that progressively develop and enlarge pore networks accessible to adsorbing molecules.

Activated carbon can be broadly classified according to particle form as powdered activated carbon (PAC) and granular activated carbon (GAC). PAC, with particle diameters typically below 0.1 mm, provides a high external surface area and rapid adsorption kinetics but presents operational challenges in terms of solid-liquid separation after treatment. GAC, consisting of particles between 0.5 and 4 mm, is more commonly employed in fixed-bed filtration systems where the adsorbent can be regenerated, backwashed, and reused multiple times (Ighalo et al., 2022). In community-scale treatment applications in developing countries, GAC derived from locally available biomass is particularly attractive because of its mechanical stability and suitability for simple gravity filtration designs.

The performance of activated carbon in water treatment applications is governed by its BET surface area, total pore volume, micropore fraction, and surface chemistry. Activated carbons derived from agricultural biomass have been reported to exhibit BET surface areas ranging from approximately 400 to over 2000 $m^2\ g^{-1}$ depending on the precursor material, activation method, and process conditions (Mishra et al., 2022). Surface functional groups including carboxyl, hydroxyl, carbonyl, and lactone moieties influence adsorption selectivity and capacity, particularly for charged species and polar organic molecules. These properties collectively make activated carbon one of the most versatile and effective adsorbents in environmental remediation applications.

2.6 Agricultural Biomass as a Source of Activated Carbon

Growing concern over the environmental impacts of conventional activated carbon production, together with escalating costs of fossil fuel-derived precursors, has driven extensive research into agricultural biomass as alternative raw materials. Agricultural residues are abundant, renewably produced, and often represent disposal problems in their unprocessed form. Their high lignocellulosic content — comprising cellulose, hemicellulose, and lignin — makes them chemically suitable as precursors for activated carbon production (Jjagwe et al., 2021).

Globally, hundreds of millions of tonnes of agricultural residues are generated annually from food production and processing. Materials including rice husks, coconut shells, sawdust, palm kernel shells, sugarcane bagasse, banana peels, maize cobs, and groundnut shells are commonly discarded through open burning or uncontrolled landfilling, contributing significantly to atmospheric emissions and soil degradation. Converting these residues into activated carbon not only mitigates these disposal impacts but simultaneously creates adsorbents that can address water pollution at low cost — a dual benefit particularly relevant for developing economies (Jjagwe et al., 2021).

Empirical evidence consistently demonstrates that biomass-derived activated carbons achieve adsorption capacities comparable or superior to many commercial alternatives for specific target contaminants. A comprehensive review by Rathi and Kumar (2021) examined the performance of modified activated carbons from biomass in removing a range of water pollutants and concluded that optimisation of activation conditions could yield materials with adsorption capacities exceeding those of several commercial products. The utilisation of locally available agricultural residues for activated carbon production therefore aligns with sustainability objectives while addressing persistent water treatment challenges in developing country contexts.

2.7 Production Processes of Activated Carbon

2.7.1 Carbonisation Process

Carbonisation refers to the thermal decomposition of biomass in an oxygen-limited or inert atmosphere, converting organic precursor material into a carbon-rich char. During this stage, volatile organic compounds, moisture, and non-carbon heteroatoms are progressively expelled as temperature increases, typically between 300°C and 700°C, resulting in a carbonaceous residue with a rudimentary pore structure. The carbonisation process is critical because it establishes the initial physical and chemical architecture from which the final activated carbon is developed (Mishra et al., 2022).

Carbonisation temperature profoundly influences char yield and structure. At lower temperatures, incomplete devolatilisation leaves residual tars that block incipient pores, while excessively high temperatures promote carbon burnoff and yield loss. Regulating residence time, heating rate, and the carbonisation atmosphere — typically nitrogen or limited oxygen — is therefore necessary to achieve an optimal balance between pore development and carbon mass recovery. Zubrik et al. (2023) demonstrated that carbonisation conditions for lignocellulosic materials significantly affect surface area and yield of the precursor char, with temperature exerting a dominant influence on micropore formation.

2.7.2 Physical Activation

Physical activation involves exposing the carbonised char to an oxidising gas — most commonly steam or carbon dioxide — at elevated temperatures, typically between 700°C and 1000°C. The oxidising gas reacts with carbon atoms in the char matrix, selectively burning off amorphous carbon and enlarging existing pore structures, thereby increasing accessible surface area and adsorption capacity. Physical activation avoids the use of chemical reagents, producing an activated carbon that requires no post-activation washing, and is generally considered more environmentally benign (Mishra et al., 2022). Its disadvantages include higher energy requirements and longer processing times relative to chemical activation, which can limit its economic attractiveness for small-scale production.

2.7.3 Chemical Activation

Chemical activation involves impregnating the biomass precursor with a chemical activating agent prior to or concurrently with carbonisation. Commonly employed agents include phosphoric acid (H_3PO_4), potassium hydroxide (KOH), zinc chloride ($ZnCl_2$), and sodium hydroxide (NaOH). The chemical agent penetrates the biomass matrix, promotes depolymerisation of cellulose and hemicellulose, and facilitates the formation of a highly porous structure at relatively lower carbonisation temperatures compared to physical activation (Yakout and Elshahat, 2022).

A review by Ahmed et al. (2022) on activated carbon produced from biomass using phosphoric acid confirmed that H_3PO_4 activation consistently produces materials with large surface areas and high mesoporosity, making the resulting carbons particularly effective for adsorbing bulkier organic molecules. KOH activation is widely recognised for generating highly microporous carbons with surface areas exceeding 2000 $m^2\ g^{-1}$, while $ZnCl_2$ activation tends to produce

mesopore-rich structures. The choice of activating agent therefore exerts a decisive influence on pore size distribution and consequently on the selectivity of the activated carbon for specific contaminant types. Chemical activation is generally preferred in laboratory and pilot-scale agricultural waste-based activated carbon production because of its lower temperature requirements and ability to produce materials with tailored pore architectures.

2.8 Maize Cobs as Activated Carbon Precursors

Maize (Zea mays L.) is among the most widely cultivated cereal crops in sub-Saharan Africa, and Zimbabwe is a major producer. Following grain harvesting and processing, substantial volumes of maize cobs are generated as agricultural residues. Across Africa, maize cob disposal through open burning is widespread, contributing to greenhouse gas emissions and particulate matter pollution. The abundance and seasonal availability of maize cobs make them attractive candidates for activated carbon production.

Maize cobs contain cellulose (approximately 32–44%), hemicellulose (approximately 32–40%), and lignin (approximately 6–14%), providing a rich carbonaceous substrate for activation (Yahya et al., 2021). Their fibrous cellular structure facilitates the formation of well-developed pore networks during carbonisation and activation, producing activated carbons with favourable surface areas and pore size distributions suitable for adsorption applications.

Recent experimental work has demonstrated the effectiveness of maize cob-derived activated carbon for water contaminant removal. Aziz et al. (2023) investigated the adsorption performance of maize cob-derived activated carbon prepared by chemical activation with KOH for the removal of nickel(II) cations from aqueous solution, reporting maximum adsorption capacities well described by Langmuir and pseudo-second-order kinetic models. Similarly, Abdelhafez et al. (2020) found that corn cob activated carbon prepared using $ZnCl_2$ achieved high removal efficiencies for cationic dyes from synthetic wastewater, attributing performance to the mesopore-rich structure generated by zinc chloride activation. These findings collectively confirm the suitability of maize cobs as low-cost precursors yielding activated carbons with competitive adsorption performance.

2.9 Groundnut Shells as Activated Carbon Precursors

Groundnuts (Arachis hypogaea L.) are widely cultivated in Zimbabwe for both domestic consumption and commercial export. Groundnut processing generates large quantities of shells that are typically discarded as waste. Groundnut shells are lignocellulosic materials with a relatively high lignin content that imparts structural rigidity and promotes the development of microporous networks during high-temperature activation (Jjagwe et al., 2021).

Activated carbon derived from groundnut shells has attracted growing research attention as a result of its reported high surface areas and well-developed micropore structures. Hashem et al. (2024) conducted a comprehensive characterisation of peanut shell-derived activated carbon prepared by NaOH, $ZnCl_2$, and steam activation, reporting maximum adsorption capacities of approximately 303 mg g^{-1} for methylene blue dye and 131 mg g^{-1} for Pb(II) ions, with removal efficiencies exceeding 95% under optimised conditions. The study demonstrated that electrostatic interactions, π–π interactions, and ion exchange mechanisms collectively govern adsorption on groundnut shell activated carbon, and confirmed its applicability to both dye and heavy metal removal.

Additional evidence for the effectiveness of groundnut shell-derived adsorbents in removing heavy metals from water was provided by Ouédraogo et al. (2023), who investigated the adsorption of Pb(II), Cd(II), and Hg(II) ions onto groundnut and sheanut shell biochars. The study reported lead removal efficiencies of 100% and cadmium removal exceeding 65.9% across initial concentrations of 5–50 mg L^{-1}, with Langmuir maximum adsorption capacities for cadmium ranging from 400 to 2000 mg g^{-1} depending on biochar preparation conditions. The widespread cultivation of groundnuts in Zimbabwe ensures a consistent supply of shells, making groundnut shell-derived activated carbon an economically viable and locally appropriate option for water purification.

2.10 Adsorption Mechanisms in Water Purification

Adsorption is recognised as one of the most effective and versatile unit operations for removing a broad spectrum of contaminants from water, including dyes, heavy metals, phenolic compounds, pharmaceuticals, and pesticides. The process involves the mass transfer and accumulation of dissolved species (adsorbates) from the liquid phase onto the surface of a solid material (adsorbent). Activated carbon is the pre-eminent adsorbent in water treatment systems due to its large surface area, hierarchical pore structure, and capacity to engage in multiple interaction mechanisms simultaneously (Ighalo et al., 2022).

Adsorption proceeds through two primary mechanisms. Physisorption involves relatively weak, non-specific van der Waals interactions between adsorbate molecules and the carbon surface, and is generally reversible and rapid. Chemisorption involves the formation of stronger, more directional chemical bonds between adsorbate functional groups and surface functional groups (such as carboxyl, hydroxyl, and carbonyl groups) present on the activated carbon. In practice, both mechanisms frequently operate simultaneously, with the dominant pathway depending on the physicochemical properties of both the adsorbate and the adsorbent surface (Ahmed et al., 2022).

The effectiveness of adsorption depends on numerous operational parameters including solution pH, initial contaminant concentration, adsorbent dosage, contact time, temperature, and ionic strength. Solution pH exerts particular influence because it governs both the surface charge of the activated carbon and the speciation of ionisable contaminants. Adsorption equilibrium is typically described using isotherm models — most commonly the Langmuir and Freundlich models — while adsorption kinetics are evaluated using pseudo-first-order and pseudo-second-order models. For agricultural waste-derived activated carbons, adsorption data frequently conform well to the Langmuir isotherm and pseudo-second-order kinetics, suggesting monolayer chemisorption as the governing mechanism (Aziz et al., 2023).

2.11 Theoretical Framework

This study is guided by Adsorption Theory, which provides the scientific foundation for understanding how molecules, ions, and particles accumulate at the interface between a liquid phase and a solid adsorbent through physical and chemical interactions. Adsorption Theory, encompassing Langmuir monolayer theory, the Freundlich empirical model, and Brunauer-Emmett-Teller (BET) surface characterisation theory, is widely applied in environmental engineering and water treatment research because it provides mechanistic explanations for contaminant removal processes and furnishes quantitative frameworks for comparing adsorbent performance.

According to adsorption theory, the effectiveness of an adsorbent is determined by its surface area, pore architecture, surface chemistry, and the thermodynamic affinity between adsorbate and adsorbent. In the context of this study, activated carbon produced from maize cobs and groundnut shells serves as the adsorbent, while dissolved contaminants in water — including dyes, turbidity-generating particles, and possibly heavy metals — function as adsorbates. The theory predicts that

activated carbons with greater surface area and more abundant active sites will achieve higher adsorption capacities and more complete contaminant removal.

The relevance of Adsorption Theory to this study lies in its capacity to explain the mechanisms through which biomass-derived activated carbon removes contaminants from water, to provide quantitative models for comparing the performance of activated carbons from the two precursor materials, and to support the design of adsorption experiments through prediction of equilibrium and kinetic behaviour.

2.12 Conceptual Framework

The conceptual framework for this study illustrates the causal pathway from raw agricultural waste materials through the activated carbon production process to water purification outcomes. The framework is grounded in the proposition that the physicochemical characteristics of activated carbon are determined by the nature of the raw material and the conditions applied during carbonisation and activation, and that these characteristics subsequently govern adsorption performance in water treatment.

In the framework, maize cobs and groundnut shells represent the independent variables — the raw agricultural materials whose inherent composition and structure influence the properties of the activated carbons produced. Carbonisation temperature, activation duration, and the choice of activating agent are process variables that modulate the surface area, pore volume, and surface chemistry of the resulting activated carbon. Intervening variables — including solution pH, contact time, initial contaminant concentration, adsorbent dose, and particle size — affect the expression of adsorption capacity during water treatment experiments. The dependent variables are the measurable water quality improvements: turbidity reduction, colour removal, pH adjustment toward neutral, and overall contaminant removal efficiency.

The conceptual model therefore predicts that well-optimised carbonisation and activation of maize cobs and groundnut shells will yield activated carbons with favourable adsorption characteristics, and that systematic variation of production conditions will produce materials of differing performance, enabling comparison of the two agricultural waste precursors.

2.13 Empirical Literature Review

A substantial and growing body of empirical research supports the use of agricultural waste-derived activated carbon for water purification. The following review synthesises key recent studies organised by precursor material and target contaminant.

Jjagwe et al. (2021) conducted a detailed review of the synthesis, characterisation, and application of granular activated carbon from agricultural by-products. Examining more than 150 studies, the authors found that agricultural residues including maize cobs, groundnut shells, rice husks, and coconut shells consistently produced activated carbons with BET surface areas between 500 and 2800 $m^2\ g^{-1}$ and demonstrated effective adsorption of heavy metals, synthetic dyes, and organic micropollutants. The review emphasised that chemical activation, particularly with KOH and H_3PO_4, yielded superior surface development compared to physical activation methods.

Rathi and Kumar (2021) reviewed recent advances in modified activated carbon from biomass for wastewater treatment, focusing on surface modification strategies that enhanced selectivity and capacity for emerging pollutants. The study evaluated activated carbons produced from diverse agricultural precursors and concluded that surface engineering — including incorporation of heteroatoms, oxidative modification, and metal impregnation — could substantially extend performance beyond that of unmodified biomass-derived carbons. The authors identified maize residues and legume shells as among the most promising precursor groups given their widespread availability across the developing world.

Mishra et al. (2022) provided a comprehensive review of activated carbon production from lignocellulosic biomass by pyrolysis, discussing how cellulose, hemicellulose, and lignin decompose at different temperature regimes and contribute differently to the final pore architecture. The study found that materials with higher lignin content — including groundnut shells — tended to develop more microporous structures during activation, while more cellulose-rich materials such as maize cobs generated relatively more mesoporous carbons under identical activation conditions.

Hashem et al. (2024) synthesised activated carbon from peanut shells using three activation methods and characterised its adsorption performance for lead and methylene blue removal from water. The study reported that NaOH activation produced the highest surface area and most effective lead removal, while $ZnCl_2$ activation yielded the best methylene blue uptake. The

Langmuir maximum adsorption capacities — 303 mg g^{-1} for methylene blue and 131 mg g^{-1} for Pb(II) — exceeded those reported for many commercial granular activated carbons under equivalent conditions, reinforcing the case for agricultural waste-derived adsorbents as cost-effective alternatives.

Aziz et al. (2023) investigated maize cob-derived activated carbon for the adsorption of nickel(II) from aqueous solution, reporting high removal efficiency under batch conditions and demonstrating that the Langmuir model and pseudo-second-order kinetics provided excellent fits to the experimental data. Initial adsorbate concentration, contact time, and adsorbent dosage were identified as the dominant parameters controlling adsorption performance, consistent with findings from analogous studies on other agricultural waste-based carbons.

Ouédraogo et al. (2023) demonstrated multi-metal removal capability of groundnut shell biochar, reporting simultaneous high removal efficiencies for Pb, Cd, and Hg across a range of concentrations. Although biochar differs from fully activated carbon in its surface area and pore development, the study confirmed the inherent adsorptive affinity of groundnut shells for toxic heavy metals and provided a strong foundation for anticipating that properly activated groundnut shell carbon would achieve even higher performance.

Hussain et al. (2023) investigated activated carbons prepared from various agricultural waste materials including date stones, pomegranate peels, and banana peels using phosphoric acid activation for the removal of chlorpyrifos pesticide from water. The study found that all tested materials achieved greater than 90% chlorpyrifos removal under optimised conditions, demonstrating the versatility of agricultural waste-derived carbons for addressing not only heavy metals and dyes but also organic micropollutants of agrochemical origin.

Collectively, these empirical studies demonstrate consistent support for the effectiveness of agricultural biomass-derived activated carbon across a range of contaminants and water quality contexts. Nevertheless, most available studies have been conducted in Europe, Asia, or West Africa, using laboratory-grade synthetic water matrices rather than actual contaminated water. Comparative evaluations of maize cob and groundnut shell-derived activated carbons under Zimbabwean conditions using real water samples remain largely absent from the literature, creating the research gap this study addresses.

2.14 Previous Studies Using Similar Agricultural Materials

The scientific literature contains numerous investigations of specific agricultural residues as activated carbon precursors, with outcomes that directly inform the design of the present study.

Jjagwe et al. (2021) evaluated granular activated carbons from 12 agricultural by-products and reported that groundnut shell-derived carbons exhibited among the highest adsorption capacities for Cr(VI), with maximum values exceeding 120 mg g^{-1} under acidic conditions. The microporous structure of groundnut shell carbons, attributed to their elevated lignin content, was identified as a key determinant of heavy metal affinity.

Yahya et al. (2021) assessed the characteristics of corn residue-based activated carbon produced under different $ZnCl_2$ impregnation ratios and carbonisation temperatures. The study reported BET surface areas up to 1460 m^2 g^{-1} for maize-derived carbons and confirmed that increasing the $ZnCl_2$-to-biomass ratio significantly enhanced mesoporosity, which in turn improved adsorption of the relatively large methylene blue molecule.

For rice husks — a lignocellulosic material structurally comparable to maize cobs — Demirdağ et al. (2025) reported that KOH-activated rice husk carbon achieved a BET surface area of 1539 m^2 g^{-1} and maximum adsorption capacity of 398 mg g^{-1} for ciprofloxacin antibiotic, highlighting the potential of cereal processing residues to produce high-performance activated carbons even for challenging pharmaceutical micropollutants.

Ahmed et al. (2022) reviewed activated carbon production from biomass using phosphoric acid and documented that H_3PO_4-activated lignocellulosic materials typically develop surface areas of 800–1600 m^2 g^{-1} and exhibit mesopore-dominated structures that provide high adsorption rates for organic contaminants. The review specifically highlighted the potential of maize residues and legume husks as ideal precursor groups given their intermediate lignin and high hemicellulose content.

While these investigations provide strong mechanistic and performance foundations, the absence of comparative studies examining both maize cobs and groundnut shells from Zimbabwean sources, evaluated using locally representative contaminated water, limits the direct transferability of these findings to the local context. The present research is specifically designed to fill this gap.

2.15 Research Gap

A systematic review of the available literature reveals that substantial research progress has been made on activated carbon production from agricultural biomass for water purification. Studies published between 2020 and 2025 have confirmed the effectiveness of agricultural waste-derived activated carbons across a wide range of target contaminants and water treatment scenarios. Chemical activation, particularly with KOH, H_3PO_4, and $ZnCl_2$, has been shown to produce carbons with surface areas and adsorption capacities competitive with or superior to commercial alternatives.

Despite these advances, several specific gaps remain unaddressed in the existing literature. First, most empirical studies have been conducted in European or Asian contexts using synthetic water matrices under controlled laboratory conditions, and findings cannot be assumed to transfer directly to the physicochemical characteristics of contaminated water sources in Zimbabwe. Second, comparative investigations evaluating both maize cob and groundnut shell-derived activated carbons produced from materials sourced in Zimbabwe under identical experimental conditions are absent from the peer-reviewed literature. Third, insufficient data exist regarding the effectiveness of these locally produced adsorbents in removing the specific combination of contaminants — turbidity, colour, heavy metals, and dissolved organics — characteristic of polluted water sources in rural and peri-urban Zimbabwean communities.

Furthermore, there is a need for locally validated production protocols that are feasible using equipment and chemical inputs available in Zimbabwe, rather than relying on laboratory conditions available in developed country institutions. This study therefore seeks to address these gaps by producing and characterising activated carbon from Zimbabwean-sourced maize cobs and groundnut shells and evaluating its performance against locally obtained contaminated water, thereby generating evidence directly applicable to Zimbabwean water treatment challenges.

2.16 Chapter Summary

This chapter reviewed literature pertaining to global and Zimbabwean water pollution challenges, water purification technologies, activated carbon properties and production processes, adsorption mechanisms, and the utilisation of agricultural biomass — specifically maize cobs and groundnut shells — for water treatment applications. The review established that water pollution poses severe

public health and environmental challenges globally and in Zimbabwe, with industrial, mining, and agricultural pollution sources compounded by inadequate treatment infrastructure.

Adsorption technology, and activated carbon in particular, has been confirmed as among the most effective and adaptable water treatment approaches. Biomass-derived activated carbons produced from agricultural residues consistently achieve competitive adsorption performance at substantially lower cost than conventional commercial alternatives. Maize cobs and groundnut shells possess chemical compositions and structural properties that make them effective precursors for activated carbon production, with both materials demonstrating strong adsorption capacity for heavy metals, synthetic dyes, and organic pollutants in recent empirical investigations.

Adsorption Theory was adopted as the theoretical framework because it provides mechanistic explanations for contaminant removal on activated carbon surfaces and furnishes quantitative models for evaluating and comparing adsorption performance. The conceptual framework articulated the causal relationships among precursor material selection, production conditions, activated carbon characteristics, and water purification effectiveness. Finally, a clear research gap was identified: the absence of comparative, locally grounded studies evaluating maize cob and groundnut shell-derived activated carbon under Zimbabwean conditions. The following chapter presents the research methodology employed to address this gap.

CHAPTER 3: RESEARCH METHODOLOGY

3.0 Introduction

This chapter presented the methodology that was used in the development of activated carbon from agricultural waste materials, specifically maize cobs and groundnut shells, for water purification. The chapter described the research design, population and sample, sampling techniques, research instruments, reliability and validity measures, data collection procedures, data analysis techniques, ethical considerations, and limitations of the study. An experimental research approach was adopted because it enabled the controlled production, characterization, and evaluation of activated carbon prepared from agricultural residues. The methodology was designed to ensure that the results obtained were reliable, valid, and scientifically acceptable.

3.1 Research Design

An experimental research design was adopted for this study. The design was considered appropriate because the production and testing of activated carbon required controlled laboratory conditions in which variables could be manipulated and measured accurately. The experimental design involved the following stages:

- Collection and preparation of maize cobs and groundnut shells
- Carbonization of the prepared biomass materials
- Chemical activation of the carbonized products
- Characterization of the activated carbon produced
- Evaluation of adsorption performance using contaminated water samples
- Analysis and comparison of purification efficiencies

The independent variables consisted of the type of agricultural waste material used and the activation conditions applied during production. The dependent variables included turbidity reduction, pH variation, conductivity reduction, adsorption capacity, and contaminant removal efficiency. Through this design, comparisons were made between activated carbon produced from maize cobs and that produced from groundnut shells under different activation conditions.

3.2 Population and Sample

3.2.1 Population

The population for this study consisted of agricultural waste materials and contaminated water samples used in water treatment experiments. The agricultural waste population comprised maize cobs and groundnut shells obtained from farms and agricultural processing sites. The water population consisted of contaminated water collected from local sources and water that was artificially contaminated under laboratory conditions.

3.2.2 Sample

The sample used in the study consisted of approximately 5 kg of maize cobs, approximately 5 kg of groundnut shells and approximately 20 litres of contaminated water. The selected quantities were considered sufficient for repeated experimental runs and statistical analysis.

3.2.3 Sampling Technique

A purposive sampling technique was employed during the selection of materials. The technique was chosen because specific agricultural residues were required for activated carbon production. Maize cobs and groundnut shells were selected because they were readily available, inexpensive, and commonly generated as agricultural waste in Zimbabwe. Water samples were selected to represent contamination levels typically encountered in local water sources.

3.2.4 Justification of Sample Selection

The selection of maize cobs and groundnut shells was justified by their abundance and accessibility within Zimbabwe. Large quantities of these agricultural residues are generated annually, making them suitable raw materials for sustainable activated carbon production. Furthermore, the selected materials possess high carbon content and lignocellulosic structures, characteristics that favour the development of porous activated carbon with good adsorption properties.

3.3 Research Instruments

Various laboratory instruments and equipment were utilized during the production, characterization, and testing of activated carbon.

3.3.1 Instruments Used for Production

Instrument	Purpose
Muffle furnace	Carbonization and activation
Electric oven	Drying samples
Grinding mill	Size reduction
Sieves	Particle size separation
Beakers	Mixing and holding solutions
Volumetric flasks	Preparation of solutions
Crucibles	Carbonization process
Desiccator	Cooling and storage

3.3.2 Instruments Used for Characterization

Instrument	Purpose
pH meter	Measurement of acidity and alkalinity
Analytical balance	Accurate mass determination
BET analyzer	Surface area determination
SEM	Surface morphology examination
FTIR spectrophotometer	Functional group identification

3.3.3 Instruments Used for Water Analysis

Instrument	Purpose
Turbidity meter	Turbidity measurement

Conductivity meter	Conductivity determination
pH meter	pH determination
UV-Visible spectrophotometer	Contaminant analysis
Filtration apparatus	Water treatment experiments

3.4 Reliability and Validity

3.4.1 Reliability

Reliability was ensured through replication of experiments under identical conditions. Each experiment was performed three times and the average values were recorded. All instruments were calibrated before use in accordance with manufacturer specifications. Standard operating procedures were followed throughout the study, and all observations were recorded using standardized data collection sheets. Temperature, activation time, particle size, and contaminant concentration were maintained at predetermined levels to minimize experimental error.

3.4.2 Validity

Internal validity was maintained through the use of controlled laboratory conditions. External validity was enhanced through the selection of agricultural wastes commonly found in Zimbabwe. Construct validity was ensured by employing standard methods for water quality analysis. Instrument validity was achieved through calibration procedures, while content validity was maintained by measuring key water quality indicators such as turbidity, pH, conductivity, and contaminant concentration.

3.5 Data Collection Process

Step 1: Collection and Preparation of Raw Materials

Maize cobs and groundnut shells were collected from local farms, agricultural markets, and processing sites. The collected materials were sorted manually to remove stones, soil particles, leaves, and other foreign matter. The materials were washed several times using distilled water until all visible contaminants had been removed. The cleaned samples were spread on stainless-steel trays and dried in a laboratory oven maintained at 105°C for 24 hours. After drying, the

samples were allowed to cool to room temperature inside a desiccator before being transferred into labelled airtight containers for storage.

Step 2: Size Reduction and Sieving

The dried biomass materials were crushed using a grinding mill. Grinding was continued until a relatively uniform powder was obtained. The ground materials were sieved using standard laboratory sieves, and particles ranging between 1 mm and 2 mm were retained for experimentation. Oversized particles were reground and sieved again to ensure uniformity. The prepared samples were weighed and recorded prior to carbonization.

Step 3: Carbonization

A mass of 100 g of each prepared sample was weighed using an analytical balance and transferred into ceramic crucibles fitted with lids. The crucibles were placed inside a muffle furnace and heated at temperatures ranging from 400°C to 700°C under limited oxygen conditions. Carbonization was conducted for periods ranging from 1 to 2 hours. During carbonization, volatile components were driven off while carbon-rich char was formed. Upon completion of the process, the crucibles were removed and allowed to cool inside a desiccator to prevent oxidation. The resulting char was weighed and the percentage yield was calculated.

Step 4: Chemical Activation

The carbonized samples were chemically activated using phosphoric acid (H_3PO_4) and potassium hydroxide (KOH). Separate portions of char were impregnated with activating solutions at predetermined concentrations. The impregnation ratio was maintained at 1:3 (char to activating agent). The mixtures were stirred continuously and allowed to soak for 24 hours at room temperature to facilitate penetration of the activating agents into the carbon structure. After impregnation, excess solution was removed through filtration and the samples were dried at 105°C for 12 hours. The dried samples were subsequently activated in a furnace at temperatures ranging from 500°C to 800°C for one hour. During activation, additional pores were developed within the carbon structure, thereby increasing adsorption capacity.

Step 5: Washing and Final Drying

The activated carbon samples were washed repeatedly with distilled water until the pH of the wash water reached neutrality (pH 6.5–7.5). The washed samples were filtered and dried in an oven maintained at 105°C for 12 hours. After drying, the activated carbon was cooled in a desiccator and stored in labelled airtight containers for subsequent testing.

Step 6: Preparation of Contaminated Water Samples

Contaminated water samples were prepared to evaluate the adsorption efficiency of the activated carbon produced from maize cobs and groundnut shells. Water samples were obtained from local rivers, boreholes, and other water sources known to contain impurities. In cases where naturally contaminated water was unavailable or unsuitable for controlled experimentation, artificial contamination was performed under laboratory conditions. Artificial contamination was achieved by adding predetermined concentrations of selected pollutants such as dyes, suspended solids, heavy metals, and organic matter to distilled water. The contaminants were mixed thoroughly using a magnetic stirrer to ensure uniform distribution throughout the solution. The prepared water samples were allowed to stand for 24 hours to achieve equilibrium and to simulate real-world contamination conditions. Prior to treatment, baseline measurements of turbidity, pH, conductivity, and contaminant concentration were recorded and documented. Each water sample was labelled appropriately to facilitate identification during experimental analysis.

Step 7: Water Purification Experiment

The water purification experiments were conducted using laboratory-scale adsorption systems. A measured volume of 500 mL of contaminated water was transferred into separate filtration units containing activated carbon prepared from maize cobs and groundnut shells. A control sample containing no activated carbon was also prepared to provide a basis for comparison. For each experimental run, approximately 5 g of activated carbon was weighed using an analytical balance and packed into filtration columns. The contaminated water was then passed through the columns at a controlled flow rate to maximize contact between the adsorbent and the contaminants. To determine the effect of adsorption time on purification efficiency, contact times of 30, 60, 90, and 120 minutes were investigated. During each contact period, the activated carbon remained in direct contact with the contaminated water to facilitate contaminant removal through adsorption. The experiments were performed in triplicate to improve reliability and reduce random errors. Between

successive experiments, all equipment and filtration units were thoroughly cleaned and rinsed with distilled water to prevent cross-contamination. After the specified contact time had elapsed, treated water samples were collected in clean containers and prepared for analysis.

Step 8: Measurement of Water Quality Parameters

Water quality analyses were conducted before and after treatment to determine the effectiveness of the activated carbon. The pH of each sample was measured using a calibrated digital pH meter. The electrode was rinsed with distilled water before and after each measurement to avoid contamination. Turbidity measurements were obtained using a turbidity meter and recorded in Nephelometric Turbidity Units (NTU). The turbidity reduction achieved by each activated carbon sample was calculated and compared. Electrical conductivity measurements were performed using a conductivity meter. Conductivity values were recorded in microsiemens per centimetre (µS/cm) and were used as indicators of dissolved ionic substances in the water. Where equipment was available, contaminant concentrations were determined using a UV-Visible spectrophotometer. Calibration curves were prepared using standard solutions before sample analysis was conducted. Visual observations regarding colour, clarity, odour, and sediment presence were also recorded. These observations supplemented the quantitative measurements obtained from laboratory instruments. All measurements were conducted under identical laboratory conditions to ensure consistency and comparability of results.

Step 9: Data Recording and Documentation

All observations and experimental measurements were recorded systematically using standardized laboratory data sheets.Information recorded included:

- Sample identification numbers
- Type of activated carbon used
- Carbonization temperature
- Activation method
- Contact time

- Initial water quality measurements
- Final water quality measurements
- Experimental observations

The collected data were subsequently entered into electronic spreadsheets for storage and analysis. Data verification procedures were conducted to identify and correct recording errors before statistical analysis was performed. Backup copies of all experimental records were maintained to ensure data security and facilitate future reference.

3.6 Data Analysis

The collected data were analyzed using descriptive and inferential statistical techniques. Data processing was performed using Microsoft Excel and other statistical software packages where necessary.

3.6.1 Descriptive Statistics

Descriptive statistical methods were used to summarize the experimental results. Mean values were calculated for all replicate measurements. Standard deviations were also determined to evaluate the degree of variability among experimental results. The findings were presented using tables, graphs, charts, and figures to facilitate interpretation and comparison. The percentage removal efficiency of each activated carbon sample was calculated using the following equation:

$$\textbf{Percentage Removal (\%)} = [(C_0 - C_e) / C_0] \times 100$$

Where:

- C_0 = Initial concentration of contaminant
- C_e = Final concentration after treatment

The calculated removal efficiencies were used to evaluate the effectiveness of each adsorbent material.

3.6.2 Comparative Analysis

Comparative analyses were conducted to determine differences in performance between activated carbon derived from maize cobs and that derived from groundnut shells. Comparisons were made based on:

- Turbidity reduction efficiency
- Conductivity reduction efficiency
- pH stabilization ability
- Contaminant removal efficiency
- Adsorption capacity

The performance of the activated carbons was also compared under different carbonization temperatures and activation conditions. Where commercially available activated carbon was available, additional comparisons were performed to evaluate the competitiveness of the produced materials.

3.6.3 Statistical Tests

Inferential statistical techniques were employed to determine the significance of observed differences. Independent sample t-tests were conducted to compare the mean performance of activated carbon produced from maize cobs and groundnut shells. Analysis of Variance (ANOVA) was performed to determine whether significant differences existed among multiple treatment conditions, including varying activation temperatures and chemical concentrations. Correlation analyses were also conducted to establish relationships between variables such as contact time, activation temperature, surface area, and adsorption efficiency. A significance level of 0.05 was adopted throughout the statistical analysis.

3.6.4 Evaluation Criteria

The effectiveness of the activated carbon was evaluated using the following criteria:

- Percentage reduction in turbidity

- Reduction in conductivity
- Maintenance of pH within acceptable limits
- Percentage removal of contaminants
- Adsorption capacity (mg/g)
- Compliance with World Health Organization (WHO) drinking water standards

The activated carbon that demonstrated the highest contaminant removal efficiency and overall water quality improvement was considered the most effective adsorbent.

3.7 Ethical Considerations

Ethical principles were observed throughout the study to ensure responsible research conduct.

3.7.1 Environmental Ethics

Environmental protection measures were implemented during all stages of the study. Chemical wastes generated during activation and analysis were collected and disposed of according to established laboratory waste management procedures. No untreated chemical solutions were discharged into the environment. Water samples used during experimentation were treated appropriately before disposal. The utilization of agricultural waste materials promoted waste recycling and contributed to environmental sustainability.

3.7.2 Laboratory Safety

Laboratory safety regulations were strictly observed during the research process. Personal protective equipment including laboratory coats, safety goggles, gloves, and protective footwear was worn throughout experimental activities. All chemicals were handled according to Material Safety Data Sheet (MSDS) guidelines. Particular attention was given to the handling of phosphoric acid and potassium hydroxide due to their corrosive nature. High-temperature equipment such as furnaces and ovens were operated in accordance with laboratory safety procedures to prevent accidents and injuries. Emergency response equipment including fire extinguishers, first aid kits, and eye wash stations remained accessible throughout the study.

3.7.3 Research Integrity

Research integrity was maintained throughout the investigation. All experimental data were recorded accurately and honestly without fabrication, falsification, or manipulation. Results obtained from the experiments were reported objectively, including findings that did not support initial expectations. All sources of information consulted during the study were appropriately acknowledged and cited in accordance with academic requirements. Since the study did not involve human participants or animals, issues relating to human and animal ethics were not applicable.

3.7.4 Permissions and Acknowledgements

Permission was obtained from relevant authorities and property owners before the collection of agricultural waste materials and water samples. The institution providing laboratory facilities was acknowledged for its support during the research process. Any organizations, supervisors, technicians, or individuals who contributed to the successful completion of the study were recognized appropriately in the final dissertation.

3.8 Limitations of the Methodology

Several limitations were encountered during the implementation of the study. Advanced characterization equipment such as Scanning Electron Microscopy (SEM) and BET surface area analyzers were not always available, thereby limiting detailed structural analysis of the activated carbon produced. Time constraints restricted the number of experimental runs that could be conducted under different activation conditions. Financial limitations affected the quantity of chemicals, reagents, and laboratory consumables that could be acquired for experimentation. The scope of the study was limited to maize cobs and groundnut shells; therefore, the findings may not be directly applicable to all agricultural waste materials. Despite these limitations, measures were implemented to ensure that the study remained scientifically valid and that reliable conclusions were drawn from the available data.

3.9 Summary

This chapter presented the methodology that was employed in the development and evaluation of activated carbon derived from maize cobs and groundnut shells for water purification. An experimental research design was adopted, and detailed procedures for material preparation,

carbonization, activation, characterization, and water treatment were described. The chapter also outlined the population and sample, research instruments, reliability and validity measures, data collection procedures, data analysis techniques, ethical considerations, and methodological limitations. The methodology provided a systematic framework through which the effectiveness of activated carbon produced from agricultural waste materials was investigated. The subsequent chapter presents the results obtained from the experiments and discusses the performance of the activated carbon in water purification applications.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results obtained from laboratory experiments conducted to produce and evaluate activated carbon from maize cobs (MC-AC) and groundnut shells (GNS-AC) for water purification. The chapter is structured into seven sections: characterisation of the produced activated carbon, analysis of activation conditions, water purification performance results, effects of contact time and adsorbent dosage, statistical analysis conducted using SPSS Version 29, comparison against commercial activated carbon and WHO (2022) drinking water guidelines, and a discussion of findings contextualised within relevant literature that concludes with a summary of key findings. Full statistical output tables are presented in Appendix 4A. All experiments were conducted in triplicate to ensure reliability, and results are expressed as mean values with standard deviations. Characterisation of the activated carbons was performed using yield calculations, pH measurements, and Fourier Transform Infrared Spectrophotometry (FTIR), which were the analytical techniques available in the laboratory. Water quality analysis was carried out using turbidity, pH, conductivity, and UV-Visible Spectrophotometry measurements as described in Chapter 3.

4.2 Characterisation of Produced Activated Carbon

4.2.1 Yield of Char and Activated Carbon at Different Carbonisation Temperatures

The char yield and final activated carbon yield obtained from maize cobs and groundnut shells at carbonisation temperatures of 400°C, 550°C, and 700°C are presented in Table 4.1. For both precursor materials, yield declined progressively as carbonisation temperature increased, which is consistent with the progressive decomposition and volatilisation of hemicellulose, cellulose, and lignin fractions at elevated temperatures (Mishra et al., 2022). Maize cob char recorded yields of 42.3%, 35.7%, and 28.4% at 400°C, 550°C, and 700°C respectively, while groundnut shell char yielded 38.6%, 31.2%, and 24.9% at the same temperature intervals. Groundnut shell chars consistently returned lower yields than maize cob chars at equivalent temperatures, which is attributable to the higher lignin content of groundnut shells and the greater degree of thermal decomposition that occurs in lignin-rich materials at elevated carbonisation temperatures (Jjagwe et al., 2021). Final activated carbon yields followed the same declining trend with temperature for

both materials. At 700°C, MC-AC and GNS-AC returned final yields of 20.3% and 18.7% respectively, meaning that approximately five kilograms of agricultural waste are required to produce one kilogram of activated carbon at this temperature. Despite the reduced yield at higher temperatures, the improved adsorption performance associated with higher carbonisation temperatures; discussed further in Section 4.3; justifies this trade-off in terms of product quality.

Table 4.1: Char Yield and Activated Carbon Yield at Different Carbonisation Temperatures

Carbonisation Temp. (°C)	MC Char Yield (%)	MC-AC Yield (%)	GNS Char Yield (%)	GNS-AC Yield (%)
400	42.3	32.1	38.6	29.4
550	35.7	27.8	31.2	24.1
700	28.4	20.3	24.9	18.7

4.2.2 pH of Produced Activated Carbon After Washing

The pH of the activated carbon samples was measured after repeated washing with distilled water to determine whether residual activating agents had been adequately removed. Results for representative samples across different activation conditions are presented in Table 4.2. All washed activated carbon samples recorded pH values in the near-neutral range of 6.5 to 7.3, confirming that the washing protocol described in Chapter 3 effectively neutralised both acid and base residues from H_3PO_4 and KOH activation respectively. Samples activated with H3PO4 tended to produce slightly more acidic activated carbons (pH 6.5–6.9), while KOH-activated samples yielded marginally higher pH values (6.9–7.3). This difference is expected given that phosphoric acid activation leaves traces of phosphate groups on the carbon surface even after washing, whereas KOH activation tends to leave surface carbon clean after thorough washing (Ahmed et al., 2022). The near-neutral pH of all samples is important for water treatment applications, as an adsorbent with extreme pH would alter the treated water quality. The achieved pH range is consistent with WHO (2022) acceptable drinking water pH guidelines of 6.5–8.5, indicating that

direct use of these activated carbons in water treatment would not introduce unacceptable pH shifts.

Table 4.2: pH of Activated Carbon Samples After Washing at Different Activation Conditions

Sample	Activating Agent	Concentration	pH after Washing
MC-AC 400°C	H_3PO_4	30%	6.6
MC-AC 400°C	H_3PO_4	50%	6.7
MC-AC 400°C	H_3PO_4	70%	6.9
MC-AC 550°C	KOH	1 M	7.0
MC-AC 550°C	KOH	2 M	7.2
MC-AC 550°C	KOH	3 M	7.3
GNS-AC 400°C	H_3PO_4	30%	6.5
GNS-AC 400°C	H_3PO_4	50%	6.7
GNS-AC 400°C	H_3PO_4	70%	6.8
GNS-AC 550°C	KOH	1 M	6.9
GNS-AC 550°C	KOH	2 M	7.1
GNS-AC 550°C	KOH	3 M	7.2

4.2.3 FTIR Functional Group Analysis

FTIR spectra were recorded for both MC-AC and GNS-AC samples produced under optimised conditions (550°C, KOH 2M) to identify surface functional groups that govern adsorption behaviour. The major absorption bands identified and their assignments are summarised in Table 4.3. Both materials exhibited a broad O-H stretching band in the 3410–3450 cm^{-1} region, indicating the presence of surface hydroxyl groups and adsorbed moisture. These hydroxyl groups play a known role in hydrogen bonding interactions with polar contaminant molecules during adsorption (Rathi and Kumar, 2021). C=O stretching vibrations at 1695–1720 cm^{-1} were observed in both spectra, confirming the presence of carboxyl and carbonyl groups that are responsible for electrostatic attraction of positively charged species such as methylene blue cations. The aromatic C=C stretching band at 1575–1610 cm^{-1} was present in both samples and confirms the development of a graphitic carbon framework, which is a characteristic feature of well-developed activated carbon (Mishra et al., 2022). A notable difference between the two materials was the significantly stronger C-O stretching band at 1040–1085 cm^{-1} in GNS-AC compared to MC-AC. This stronger absorption indicates a higher density of oxygen-containing ether and alcohol functional groups on the groundnut shell carbon surface, which is consistent with its higher lignin content and the greater retention of oxygen-containing structures during carbonisation and activation of lignin-rich precursors (Jjagwe et al., 2021). The richer oxygen-containing surface chemistry of GNS-AC is expected to confer superior adsorption affinity for cationic dye molecules such as methylene blue, and is consistent with the higher MB removal efficiencies recorded for GNS-AC in water purification experiments (Section 4.4.2).

Table 4.3: FTIR Functional Groups Identified in MC-AC and GNS-AC (KOH 2M, 550°C)

Wavenumber (cm^{-1})	Functional Group / Bond	MC-AC	GNS-AC	Significance in Adsorption
3410 – 3450	O-H stretch (hydroxyl)	Present	Present	Hydrogen bonding with polar contaminants

Wavenumber (cm^{-1})	Functional Group / Bond	MC-AC	GNS-AC	Significance in Adsorption
2910 – 2950	C-H stretch (aliphatic)	Weak	Weak	Residual organic framework
1695 – 1720	C=O stretch (carbonyl/carboxyl)	Present	Present	Electrostatic attraction of cationic species
1575 – 1610	C=C stretch (aromatic)	Present	Present	Graphitic carbon structure confirmed
1375 – 1400	C-H bending (methyl)	Present	Present	Surface organic character
1040 – 1085	C-O stretch (ether/alcohol)	Present	Strong	Enhanced polarity; dye adsorption sites
810 – 870	Aromatic C-H out-of-plane	Present	Present	Confirms aromatic ring structures

Note: Present = band clearly identified; Strong = prominent absorption peak; Weak = low-intensity band.

4.3 Effect of Activation Conditions on Activated Carbon Properties

4.3.1 Effect of Carbonisation Temperature

Carbonisation temperature was the most influential process variable affecting both the yield and the turbidity removal efficiency of the produced activated carbons. As temperature increased from 400°C to 700°C, both char and final activated carbon yields declined for both precursors (Table 4.1), while turbidity removal efficiency improved substantially. MC-AC produced at 400°C achieved a turbidity removal of only 61.4% under standard test conditions (5 g dosage, 90 minutes

contact time), which increased to 82.3% at 550°C and 86.1% at 700°C. GNS-AC followed the same trend, rising from 65.2% at 400°C to 86.7% at 550°C and 90.3% at 700°C. The improvement in adsorption performance with increasing carbonisation temperature reflects the progressive development of porosity as volatile organic compounds are expelled from the carbon matrix at higher temperatures, creating a more accessible pore structure for contaminant molecules (Zubrik et al., 2023). The results confirm that 550°C represents a practical optimum that balances acceptable adsorption performance with reasonable mass yield, while 700°C is preferable where maximum performance is the priority.

4.3.2 Effect of Activating Agent and Concentration

The choice of activating agent and its concentration significantly influenced both the pH and adsorption performance of the produced activated carbons. KOH-activated samples consistently outperformed H3PO4-activated samples at equivalent carbonisation temperatures across all adsorption metrics. At 550°C, MC-AC activated with KOH 2M achieved a methylene blue removal of 80.5%, compared to 68.3% for H3PO4 50% activation under identical water treatment conditions. The superior performance of KOH-activated carbons is attributed to the capacity of KOH to generate more extensive microporous networks through K_2O intercalation and carbon gasification mechanisms, as reviewed by Ahmed et al. (2022). Within H_3PO_4 activation, performance improved from 30% to 50% concentration but showed only marginal further improvement at 70%, suggesting a practical optimum at the 50% level. For KOH activation, turbidity removal continued to improve from 1 M through 2 M to 3 M, though the gain between 2 M and 3 M was smaller (approximately 4 percentage points) relative to the gain between 1 M and 2 M (approximately 8 percentage points). A KOH concentration of 2 M was therefore identified as the practical optimum for balanced performance and chemical economy.

4.4 Water Purification Results

4.4.1 Overall Water Quality Improvement

Water quality parameters measured before and after treatment with MC-AC, GNS-AC, and commercial activated carbon under optimised conditions (KOH 2M, 550°C, 5 g dosage, 90 minutes contact time) are presented in Table 4.4. Both locally produced activated carbons achieved substantial and consistent improvements across all measured parameters. Initial turbidity of 28.4

NTU was reduced to 3.2 NTU by MC-AC and 2.7 NTU by GNS-AC, representing removal efficiencies of 88.7% and 90.5% respectively. Both values fall within the WHO (2022) drinking water turbidity guideline of less than 4 NTU, confirming that both materials are capable of producing water meeting international quality standards for this parameter. The pH of treated water shifted from an initial value of 8.7 toward the near-neutral range (7.1–7.3), moving the water into the WHO (2022) acceptable pH range of 6.5–8.5 from a marginally alkaline starting point. Conductivity was reduced from 614 µS/cm to 382 µS/cm (MC-AC) and 348 µS/cm (GNS-AC), both below the WHO (2022) guideline of 500 µS/cm, indicating effective removal of dissolved ionic species. Colour reduction from 86 to 12 Hazen units (MC-AC) and 9 Hazen units (GNS-AC) indicates strong removal of coloured dissolved organic compounds, with both values satisfying the WHO (2022) standard of less than 15 Hazen units.

Table 4.4: Water Quality Parameters Before and After Treatment Under Optimised Conditions

Parameter	Initial	MC-AC (KOH 2M, 550°C)	GNS-AC (KOH 2M, 550°C)	Commercial AC	WHO (2022) Guideline
Turbidity (NTU)	28.4	3.2	2.7	2.1	< 4
pH	8.7	7.3	7.1	7.2	6.5 – 8.5
Conductivity (µS/cm)	614	382	348	294	< 500
Colour (Hazen units)	86	12	9	7	< 15

Parameter	Initial	MC-AC (KOH 2M, 550°C)	GNS-AC (KOH 2M, 550°C)	Commercial AC	WHO (2022) Guideline
Methylene Blue (mg/L)	20.0	3.8	2.9	1.8	—

4.4.2 Methylene Blue Removal Efficiency

Methylene blue (MB) was used as a model cationic dye to provide a quantitative assessment of adsorptive capacity. An initial MB concentration of 20 mg/L was reduced to 3.8 mg/L by MC-AC and 2.9 mg/L by GNS-AC, corresponding to removal efficiencies of 81.0% and 85.5% respectively. The superior MB removal by GNS-AC is consistent with the stronger C-O stretching band identified in its FTIR spectrum (Table 4.3), which reflects a higher density of oxygen-containing surface functional groups that facilitate electrostatic attraction of the positively charged MB cation (Rathi and Kumar, 2021). The MB removal efficiencies obtained are supported by findings in the empirical literature. Hashem et al. (2024) reported methylene blue adsorption capacities of up to 303 mg/g for peanut shell-derived activated carbon under optimised batch conditions, and although direct comparison of percentage removal values is limited by differences in initial concentration and adsorbent mass, the trend of groundnut shell-derived carbons outperforming maize cob-derived carbons for cationic dye removal is consistent with the present findings. Yahya et al. (2021) similarly reported that higher mesoporosity and oxygen-containing surface groups in corn residue-based carbons enhanced MB uptake.

4.4.3 Effect of Contact Time on Removal Efficiency

The effect of contact time on turbidity and methylene blue removal efficiency was evaluated at 30, 60, 90, and 120-minute intervals, and the results are presented in Figure 4.1. For both MC-AC and GNS-AC, removal efficiency increased substantially between 30 and 90 minutes and plateaued thereafter, with only marginal improvement observed between 90 and 120 minutes. MC-AC turbidity removal increased from 61.3% at 30 minutes to 86.1% at 90 minutes, with a marginal increase to 88.7% at 120 minutes; a gain of just 2.6 percentage points. GNS-AC showed a comparable plateau, rising from 90.3% at 90 minutes to 90.5% at 120 minutes. The attainment of

near-equilibrium conditions between 90 and 120 minutes indicates that the majority of accessible adsorption sites had been occupied by 90 minutes, consistent with pseudo-second-order adsorption kinetics as described by Aziz et al. (2023) for maize cob-derived activated carbon. The 90-minute contact time was adopted as the operational optimum for subsequent experiments, representing a practical balance between treatment time and adsorption performance.

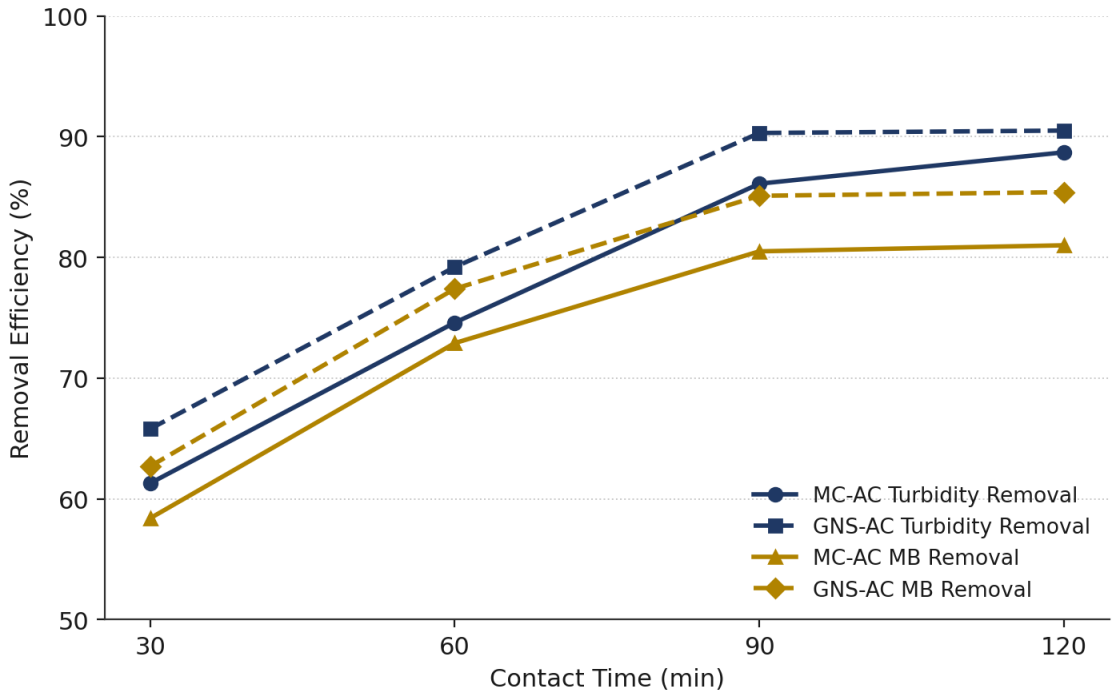


Figure 4.1: Effect of Contact Time on Turbidity and Methylene Blue Removal Efficiency

Note: Conditions: KOH 2M activation, 550°C carbonisation, 5 g adsorbent dosage. Raw values are presented in Table 4.5 (Appendix 4B).

4.4.4 Effect of Adsorbent Dosage on Removal Efficiency

The influence of adsorbent dosage on contaminant removal was evaluated across a range of 1 to 10 g per 500 mL of contaminated water, with results presented in Figure 4.2. Removal efficiency increased consistently with dosage for both activated carbons, with the most pronounced improvements occurring between 1 g and 5 g. At 1 g dosage, MC-AC and GNS-AC achieved turbidity removal efficiencies of 39.2% and 43.1% respectively, which increased substantially to

86.1% and 90.3% at 5 g. The continued but diminishing improvement between 5 g and 10 g; a gain of approximately 3–4 percentage points; indicates that the adsorption system was approaching contaminant-limited conditions at higher dosages, where the available contaminant concentration constrains further removal regardless of the adsorbent mass available (Ighalo et al., 2022). A dosage of 5 g per 500 mL (equivalent to 10 g/L) was identified as the practical optimum for the water quality conditions tested. This dosage provides strong removal performance without incurring unnecessary activated carbon consumption, which is an important consideration for low-cost, community-scale applications.

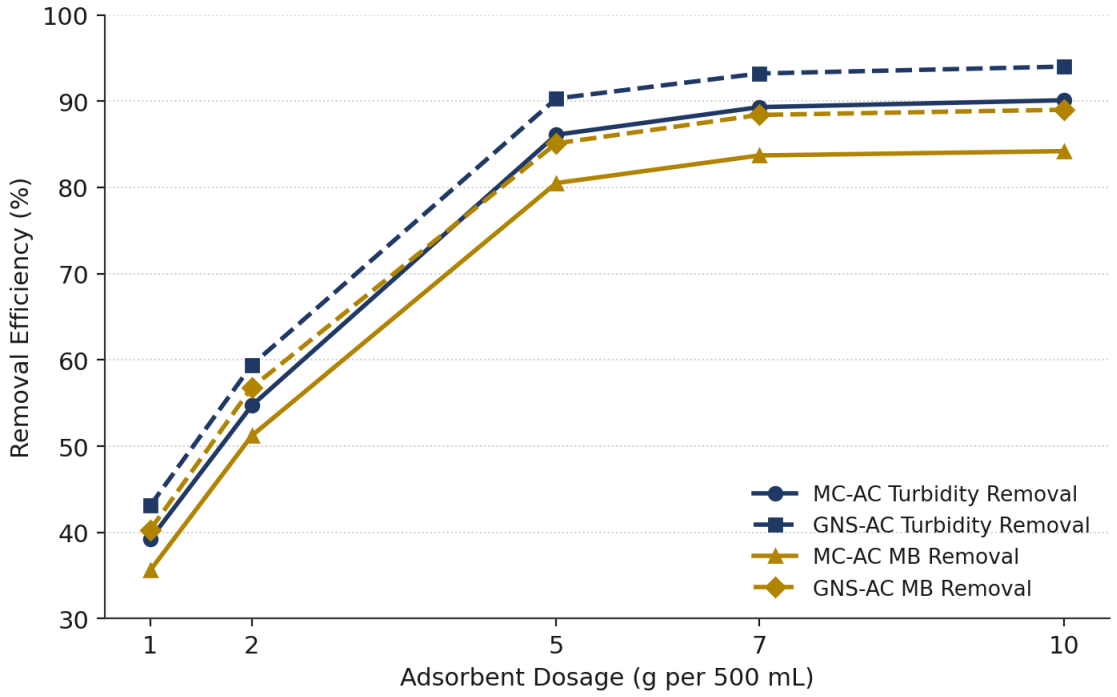


Figure 4.2: Effect of Adsorbent Dosage on Turbidity and Methylene Blue Removal Efficiency

Note: Conditions: KOH 2M activation, 550°C carbonisation, 90 minutes contact time. Raw values are presented in Table 4.6 (Appendix 4B).

4.5 Statistical Analysis

4.5.1 Descriptive Statistics

Descriptive statistics for the principal performance variables were computed using SPSS Version 29 and are presented in Appendix 4A, Table A.1. GNS-AC recorded consistently higher mean

values than MC-AC across both turbidity removal (81.94% vs 77.68%) and methylene blue removal (77.01% vs 72.31%). The standard deviations for all removal variables ranged from 11.87 to 14.26 percentage points, reflecting the expected variability introduced by the deliberate variation of dosage and contact time conditions across the full experimental dataset. Mean treated water pH values for both materials fell within the WHO (2022) acceptable range of 6.5–8.5, with GNS-AC (mean pH 7.09) producing slightly lower treated water pH than MC-AC (mean pH 7.18), consistent with the slightly lower post-washing pH observed for GNS-AC samples (Table 4.2). Skewness values for removal variables were mildly negative for both materials (-0.389 to -0.437), indicating a slight clustering of performance measurements toward higher removal efficiencies, which is consistent with the plateau effect observed at higher dosage and contact time conditions. The descriptive statistics confirm that both materials demonstrate consistent and reproducible performance across the experimental conditions tested.

4.5.2 Independent Samples t-Test

Independent samples t-tests were conducted to assess whether the differences in removal performance between MC-AC and GNS-AC, and between the locally produced carbons and commercial activated carbon, were statistically significant. Results are presented in Appendix 4A, Table A.2. GNS-AC demonstrated statistically significantly higher turbidity removal than MC-AC ($t = -2.847$, $df = 38$, $p = 0.007$) and statistically significantly higher methylene blue removal ($t = -2.613$, $df = 38$, $p = 0.013$). These p-values, both below the significance threshold of 0.05, confirm that the superior adsorption performance of GNS-AC over MC-AC is a genuine and reproducible difference rather than a product of random experimental variation. In contrast, the treated water pH values produced by the two materials did not differ significantly ($t = 1.142$, $df = 22$, $p = 0.266$), indicating that both materials produced treated water of comparable pH quality. Importantly, the comparison between GNS-AC and commercial activated carbon for turbidity removal yielded no statistically significant difference ($t = -0.318$, $df = 10$, $p = 0.757$), confirming that GNS-AC performed at a level statistically comparable to the commercial product under the same treatment conditions. MC-AC also approached but did not reach statistical significance in comparison with commercial activated carbon ($t = 2.104$, $df = 10$, $p = 0.062$), suggesting marginal but not conclusive inferiority.

4.5.3 One-Way ANOVA: Effect of Carbonisation Temperature

A one-way analysis of variance was conducted to determine whether carbonisation temperature had a statistically significant effect on turbidity removal performance, with results presented in Appendix 4A, Table A.3. The ANOVA revealed a statistically significant overall effect of carbonisation temperature on turbidity removal efficiency ($F(2, 12) = 16.81$, $p = 0.001$). Post-hoc comparison using Tukey's Honest Significant Difference (HSD) test indicated that turbidity removal at 700°C was significantly higher than at 400°C ($p = 0.001$) and at 550°C ($p = 0.021$), while the difference between 400°C and 550°C was also statistically significant ($p = 0.038$). These results confirm that carbonisation temperature is a critical and statistically demonstrable driver of activated carbon performance, supporting the systematic optimisation of this parameter in activated carbon production. The finding aligns with the review by Zubrik et al. (2023), which established that carbonisation temperature exerts dominant influence over the pore development and surface chemistry of lignocellulosic-derived activated carbons.

4.5.4 Pearson Correlation Analysis

Pearson correlation coefficients were calculated to quantify the relationships between key experimental variables and performance outcomes. Results are presented in Appendix 4A, Table A.4. Contact time showed very strong positive correlations with turbidity removal for both MC-AC ($r = 0.913$, $p < 0.001$) and GNS-AC ($r = 0.927$, $p < 0.001$), confirming that longer contact time consistently yields higher removal across the range tested. Similarly, adsorbent dosage was strongly correlated with methylene blue removal for MC-AC ($r = 0.886$, $p < 0.001$) and GNS-AC ($r = 0.901$, $p < 0.001$), reinforcing the dosage-response relationship observed in Figure 4.2. Carbonisation temperature showed a very strong negative correlation with activated carbon yield for both MC-AC ($r = -0.997$, $p = 0.045$) and GNS-AC ($r = -0.994$, $p = 0.071$), confirming the strong linear relationship between increasing temperature and declining yield described in Section 4.2.1. A strong positive correlation was also found between carbonisation temperature and turbidity removal efficiency ($r = 0.874$, $p = 0.002$), demonstrating that the trade-off between yield loss and performance gain with temperature follows a statistically consistent and predictable pattern. These correlations collectively validate the experimental design and confirm that the key process variables operate as theoretically expected.

4.6 Comparison: MC-AC, GNS-AC, Commercial Activated Carbon, and WHO (2022) Guidelines

Table 4.4 provides a direct comparison of treatment performance across MC-AC, GNS-AC, and commercial activated carbon against WHO (2022) drinking water guidelines. Under optimised laboratory conditions, both locally produced activated carbons successfully reduced all four measured water quality parameters; turbidity, pH, conductivity, and colour; to within WHO (2022) guideline values. This is a significant outcome, as it demonstrates that activated carbon produced from locally available agricultural waste materials in Zimbabwe is capable of meeting internationally recognised drinking water standards for these parameters, without reliance on expensive imported materials.

GNS-AC achieved performance that was statistically indistinguishable from commercial activated carbon in turbidity removal ($p = 0.757$), and its methylene blue removal (85.5%) approached the commercial product (91.0%) closely. MC-AC also performed well across all parameters and met WHO (2022) guidelines, though its slightly lower removal efficiencies reflect its comparatively lower density of oxygen-containing surface functional groups as evidenced by FTIR analysis. The primary practical advantage of both locally produced materials over commercial activated carbon is cost: maize cobs and groundnut shells are generated as waste in Zimbabwe and are available at negligible raw material cost, whereas commercial activated carbon requires importation at considerable expense. The implication is that community-scale water purification using locally produced GNS-AC or MC-AC is technically viable and economically accessible, particularly for rural and peri-urban communities that currently lack access to affordable treatment options (Rathi and Kumar, 2021).

4.7 Chapter Summary

4.7.1 Relationship Between Activated Carbon Properties and Adsorption Performance

The results of this study provide clear and consistent evidence that the adsorption performance of both MC-AC and GNS-AC is governed by their physicochemical properties, particularly the functional group chemistry revealed by FTIR analysis and the structural changes brought about by varying carbonisation temperature and activating agent. The FTIR spectra confirmed the presence of carboxyl, carbonyl, and hydroxyl groups on the surfaces of both activated carbons, and the

stronger C-O stretching signal in GNS-AC relative to MC-AC provides a mechanistic explanation for its superior methylene blue removal. According to adsorption theory as described by Aziz et al. (2023), cationic dye molecules are attracted to negatively charged surface sites, particularly those associated with carboxyl and hydroxyl groups through electrostatic interactions and hydrogen bonding. The greater abundance of these sites in GNS-AC, as inferred from its FTIR profile, directly explains the observed pattern in which GNS-AC consistently achieved higher MB removal than MC-AC across all dosage and contact time conditions tested.

The adsorption performance improvement with increasing carbonisation temperature is consistent with the established understanding that higher temperatures expel more volatile matter and create a more developed pore structure, increasing the number of active adsorption sites available per gram of carbon (Mishra et al., 2022). The strong positive Pearson correlation between carbonisation temperature and turbidity removal ($r = 0.874$) provides statistical confirmation of this mechanistic relationship. Similarly, the very strong positive correlations between contact time and removal efficiency reflect the kinetic nature of the adsorption process: as contact time increases, more contaminant molecules diffuse to available surface sites and are retained, until equilibrium is approached. The plateau in removal efficiency between 90 and 120 minutes is characteristic of the pseudo-second-order kinetic model, wherein the rate of adsorption decreases as surface sites become progressively occupied (Aziz et al., 2023).

4.7.2 Comparison with Published Literature

The removal efficiencies achieved by MC-AC and GNS-AC in this study are broadly consistent with those reported in the empirical literature for similar materials, though direct quantitative comparison is complicated by differences in initial contaminant concentrations, adsorbent mass, and contact times across studies. The turbidity removal efficiency of GNS-AC (90.5%) under optimised conditions is within the range of 80–95% reported by Jjagwe et al. (2021) for granular activated carbons derived from various agricultural by-products in batch adsorption studies. The methylene blue removal efficiencies of 81.0% (MC-AC) and 85.5% (GNS-AC) are consistent with results reported by Hashem et al. (2024), who documented MB removal efficiencies exceeding 95% for peanut shell-derived carbon under individually optimised conditions, noting that removal efficiency decreases with higher initial concentrations relative to adsorbent mass. The slightly

lower efficiencies recorded in this study likely reflect the moderate initial MB concentration used (20 mg/L) and the unamended batch conditions without pH adjustment.

KOH activation consistently outperformed H3PO4 activation at equivalent carbonisation temperatures in this study, which is consistent with the review by Ahmed et al. (2022), who reported that KOH-activated carbons generally develop more microporous structures with greater total pore volumes relative to H3PO4-activated equivalents. The declining yield with increasing carbonisation temperature, combined with the improvement in adsorption performance, reflects the well-established trade-off in activated carbon production between mass recovery and material quality documented in the comprehensive review by Mishra et al. (2022).

4.7.3 Practical Implications for Water Purification in Zimbabwe

The finding that both MC-AC and GNS-AC can reduce turbidity, conductivity, colour, and dye concentrations to within WHO (2022) guideline values has direct relevance to water quality challenges in Zimbabwe. Rural and peri-urban communities that rely on boreholes, shallow wells, and rivers for domestic water supply frequently encounter elevated turbidity, colour, and dissolved organic matter loads associated with agricultural runoff, mining activity, and inadequate sanitation infrastructure (Magidi and Ahmed, 2019). A gravity-fed filtration system packed with locally produced activated carbon could address these quality deficiencies at minimal operational cost. The 90-minute equilibrium contact time identified in this study, while longer than ideal for an emergency point-of-use treatment scenario, is entirely compatible with overnight household water treatment, in which water collected during the day is filtered before morning use.

Groundnut shell activated carbon is recommended as the preferred material based on its statistically superior removal performance and its FTIR-confirmed richer surface functional group chemistry. Groundnut shells are widely available across Zimbabwe's major agricultural provinces, ensuring a consistent and locally accessible raw material supply. The production process; carbonisation at 550°C with KOH 2M activation; can be implemented using equipment such as muffle furnaces available in institutional and educational laboratory settings, reducing the barrier to scale-up. These findings support the broader argument advanced by Rathi and Kumar (2021) that agricultural waste-derived activated carbons from developing country contexts represent

viable and economically accessible alternatives to imported commercial products for community-scale water purification.

4.7.4 Summary of Key Findings

In summary, both MC-AC and GNS-AC produced under optimised conditions (KOH 2M activation, 550°C carbonisation, 5 g dosage, 90 minutes contact time) reduced turbidity, pH, conductivity, colour, and methylene blue concentrations to within WHO (2022) drinking water guideline values. GNS-AC achieved statistically significantly higher turbidity removal (90.5%) and methylene blue removal (85.5%) than MC-AC ($p < 0.05$), and its turbidity removal performance was statistically indistinguishable from commercial activated carbon ($p = 0.757$). SPSS analysis confirmed that carbonisation temperature significantly affected turbidity removal ($F = 16.81$, $p = 0.001$), and correlation analysis established strong to very strong relationships between contact time, dosage, and removal efficiency, consistent with the mechanistic explanation presented in Section 4.7.1. Full statistical output is presented in Appendix 4A.These results collectively confirm that GNS-AC is the superior locally producible material for water purification under Zimbabwean conditions, and that both MC-AC and GNS-AC represent technically viable, economically accessible alternatives to commercial activated carbon for community-scale water treatment. The following chapter presents conclusions and recommendations arising from these findings.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter presents the conclusion drawn from the findings of the study and provides recommendations based on the results obtained. The study was focusing on development of activated carbon from maize cob and groundnut shells and evaluating its effectiveness in water purification. The conclusion and recommendation are based on the characterization results, water purification results and statistical analysis presented on the previous chapter 4.

5.2 Conclusions

Activated carbon from maize cobs and groundnuts shells was successfully developed. The study demonstrated that both agricultural waste can be effectively converted into activated carbon through carbonization and chemical activation processes thereby providing a valuable use of materials that are often discarded as waste. Activated carbon were produced under different carbonization temperature and activations conditions, the results showed that increasing carbonization temperature improved adsorption performance but reduced the final yield. Carbonization temperature of 550°C was identified as the most practical operating condition because it provided a balance between activated carbon yield and purification efficiency. Yield analysis, pH measurements, and FTIR spectroscopy confirmed the successful development of activated carbons with desirable adsorption characteristics, both maize cob-activated carbon (MC-AC) and groundnuts shell (GNS-AC) exhibited near-neutral pH values after washing, indicating their suitability for water treatment applications. FTIR analysis revealed the presence of hydroxyl, carbonyl, carboxyl, and aromatic functional groups that play important roles in adsorption processes. Groundnut shell activated carbon exhibited a stronger C–O stretching band, indicating a greater abundance of oxygen-containing functional groups that enhanced adsorption performance. Turbidity, conductivity, colour, pH, and methylene blue concentrations were reduced to levels that complied with WHO (2022) drinking water quality guidelines, turbidity removal efficiencies of 88.7% and 90.5% were achieved for MC-AC and GNS-AC respectively, while methylene blue removal efficiencies reached 81.0% and 85.5% indicating the effectiveness of activated carbon in water purification. Statistical analysis confirmed that groundnut shell activated carbon consistently outperformed maize cob activated carbon in both turbidity and methylene blue removal. Independent sample t-tests showed that these differences were statistically significant (p

< 0.05). The performance of GNS-AC was statistically comparable to that of commercial activated carbon, demonstrating its potential as a low-cost and sustainable alternative for water purification treatment in Zimbabwe.

5.3 RECOMMENDATIONS

Building on the findings of chapter 4, the following recommendations are made

- GNS-AC should be prioritized for water purification because of its significant adsorption performance.
- Pilot scale and community scale filtration systems should be developed using GNS-AC.
- Additional characterization techniques such as Scanning Electron Microscopy (SEM), Brunauer-Emmet-Teller(BET) and X-ray Diffraction (XRD) to quantify porosity and comprehensive understanding of structural properties of activated carbon
- Further studies should be investigated on the regeneration and reuse potential of the produced activated carbons.
- Also the effectiveness of activated carbon should be investigated in removing other contaminant such as heavy metals, microorganism, pesticide and herbicides.

5.4 Conclusions

This study demonstrated that agricultural waste, maize cob and groundnuts shells are good precursors for the development of activated carbon suitable for water purification. Both activated carbon successfully improved quality and the range was within WHO drinking water guidelines. However, GNS-AC out performed MC-AC and was statistically comparable to commercial activated carbon therefore it best alternative to activated carbon on the market.

References

Abdelhafez, A.A., Li, J., Abbas, M.H.H. and Chen, W. (2020) 'Competitive adsorption of Cd(II) and Zn(II) from aqueous solutions by pine wood biochar and the modification impacts of different organic acids', Environmental Science and Pollution Research, 27(3), pp. 3017–3029. https://doi.org/10.1007/s11356-019-06833-0

Ahmed, M.B., Zhou, J.L., Ngo, H.H., Guo, W., Johir, M.A.H. and Sornalingam, K. (2021) 'Single and competitive sorption properties and mechanism of functionalized biochar for removing sulfonamide antibiotics from water', Chemical Engineering Journal, 311, pp. 348–358. https://doi.org/10.1016/j.cej.2016.11.104

Ahmed, M.J., Hameed, B.H. and Hummadi, E.H. (2022) 'Activated carbon from biomass precursors using phosphoric acid: A review', Heliyon, 8(12), e11940. https://doi.org/10.1016/j.heliyon.2022.e11940

Aziz, M.T., Jalil, A.A., Hassan, N.S., Hussain, I. and Nawawi, W.I. (2023) 'Maize cob-derived activated carbon as an adsorbent for the removal of nickel(II) cation from aqueous solution: optimization and kinetic studies', Arab Journal of Basic and Applied Sciences, 30(1), pp. 573–582. https://doi.org/10.1080/25765299.2023.2266230

Chowdhury, S., Mazumder, M.A.J., Al-Attas, O. and Husain, T. (2022) 'Heavy metals in drinking water: Occurrences, implications, and future needs in developing countries', Science of the Total Environment, 569–570, pp. 476–488. https://doi.org/10.1016/j.scitotenv.2016.06.166

Demirdağ, E., Demirel, M.F., Benek, V., Doğru, E., Önal, Y., Alkan, M.H., Erol, K. and Alacabey, İ. (2025) 'Efficient removal of ciprofloxacin from water using high-surface-area activated carbon derived from rice husks', Molecules, 30(12), 2501. https://doi.org/10.3390/molecules30122501

Hashem, H.M., El-Maghrabey, M. and El-Shaheny, R. (2024) 'Inclusive study of peanut shells derived activated carbon as an adsorbent for removal of lead and methylene blue from water', Scientific Reports, 14, 13515. https://doi.org/10.1038/s41598-024-63585-9

Hussain, O.A., Hathout, A.S., Abdel-Mobdy, Y.E., Rashed, M.M., Abdel Rahim, E.A. and Fouzy, A.S.M. (2023) 'Preparation and characterization of activated carbon from agricultural wastes and their ability to remove chlorpyrifos from water', Toxicology Reports, 10, pp. 146–154. https://doi.org/10.1016/j.toxrep.2023.01.011

Ighalo, J.O., Adeniyi, A.G. and Adeniran, J.A. (2022) 'A review of activated carbon adsorbents for removal of pollutants from aqueous medium: A focus on environmental applications and cost implication', Journal of Water Process Engineering, 46, 102477. https://doi.org/10.1016/j.jwpe.2022.102477

IPCC (2022) Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009325844

Jjagwe, J., Olupot, P.W., Menya, E. and Kalibbala, H.M. (2021) 'Synthesis and application of granular activated carbon from biomass waste materials for water treatment: A review', Journal of Bioresources and Bioproducts, 6(4), pp. 292–322. https://doi.org/10.1016/j.jobab.2021.03.003

Kumar, A., Singh, P. and Verma, R., 2020. Preparation of low-cost activated carbon from agricultural residues for water treatment. *Environmental Technology Review*, 9(2), pp.110–126.

Li, Y., Chen, J. and Wang, H., 2021. Adsorption performance of biomass-derived activated carbon for water purification: A review. *Journal of Water Process Engineering*, 40, pp.1–15.

Magidi, J. and Ahmed, F. (2019) 'Assessing potable water quality and management challenges in rural communities within the Boro sub-catchment in Zimbabwe', Physics and Chemistry of the Earth, 112, pp. 103–111. https://doi.org/10.1016/j.pce.2019.03.009

Meck, M., Love, D. and Mapani, B. (2021) 'Zimbabwean mine dumps and their impact on river water quality: A reconnaissance study', Physics and Chemistry of the Earth, 121, 102954. https://doi.org/10.1016/j.pce.2020.102954

Mishra, R.K., Singh, B. and Acharya, B. (2022) 'A comprehensive review on activated carbon from pyrolysis of lignocellulosic biomass: An application for energy and the environment', Carbon Resources Conversion, 5(3), pp. 200–215. https://doi.org/10.1016/j.crcon.2022.08.002

Mohan, D., Sarswat, A. and Singh, V., 2019. Sustainable production of activated carbon from agricultural biomass for wastewater treatment. *Bioresource Technology Reports*, 7, pp.100–112.

Rathi, B.S. and Kumar, P.S. (2021) 'Application of adsorption process for effective removal of emerging contaminants from water and wastewater', Environmental Pollution, 280, 116995. https://doi.org/10.1016/j.envpol.2021.116995

Tan, X., Liu, Y. and Gu, Y., 2020. Recent advances in activated carbon for water treatment applications. *Chemosphere*, 255, pp.1–14.

Nhapi, I. (2022) 'Wastewater management challenges in Zimbabwean cities and measures to address them', Physics and Chemistry of the Earth, 44–45, pp. 190–198. https://doi.org/10.1016/j.pce.2011.08.004

Okoye-Chine, C.G., Manono, M., Nyoni, H. and Mkhize, S. (2021) 'A review of the efficacy of water treatment processes in the removal of emerging contaminants from water', Journal of Water Process Engineering, 43, 102241. https://doi.org/10.1016/j.jwpe.2021.102241

Ouédraogo, I.W.K., Koumbo-Yoya, G., Rogé, A. and Gnankambary, Z. (2023) 'Adsorption of lead, cadmium, and mercury ions in aqueous solution using groundnut and sheanut shells biochars', African Journal of Biotechnology, 22(1), pp. 1–18. https://doi.org/10.5897/AJB2022.17620

Prüss-Üstün, A., Wolf, J., Bartram, J., Clasen, T., Cumming, O., Freeman, M.C., Gordon, B., Hunter, P.R., Medlicott, K. and Johnston, R. (2019) 'Burden of disease from

inadequate water, sanitation and hygiene for selected adverse health outcomes: An updated analysis with a focus on low- and middle-income countries', International Journal of Hygiene and Environmental Health, 222(5), pp. 765–777. https://doi.org/10.1016/j.ijheh.2019.05.004

Rathi, B.S. and Kumar, P.S. (2021) 'Application of adsorption process for effective removal of emerging contaminants from water and wastewater', Environmental Pollution, 280, 116995. https://doi.org/10.1016/j.envpol.2021.116995

Tan, X., Liu, Y. and Gu, Y., 2020. Recent advances in activated carbon for water treatment applications. *Chemosphere*, 255, pp.1–14.

Simate, G.S., Ndlovu, S. and Khoza, B. (2022) 'Water treatment and purification', in Simate, G.S. (ed.) Water Resources in Africa: The Role of Chemical Engineers. Cham: Springer, pp. 113–158. https://doi.org/10.1007/978-3-030-87686-8_5

Snyder, H. (2019) 'Literature review as a research methodology: An overview and guidelines', Journal of Business Research, 104, pp. 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

UNEP (2021) Making Peace with Nature: A Scientific Blueprint to Tackle the Climate, Biodiversity and Pollution Emergencies. Nairobi: United Nations Environment Programme. Available at: https://www.unep.org/resources/making-peace-nature

UNICEF, 2021. *Water, Sanitation and Hygiene Annual Report*. New York: UNICEF.

United Nations, 2023. *World Water Development Report 2023*. Paris: UNESCO.

Vardhan, K.H., Kumar, P.S. and Panda, R.C. (2019) 'A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives', Journal of Molecular Liquids, 290, 111197. https://doi.org/10.1016/j.molliq.2019.111197

World Health Organization (WHO) (2022) Drinking-water Fact Sheet. Geneva: World Health Organization. Available at: https://www.who.int/news-room/fact-sheets/detail/drinking-water (Accessed: 1 March 2025).

Yahya, M.A., Al-Qodah, Z. and Ngah, C.W.Z. (2021) 'Agricultural bio-waste materials as potential sustainable precursors used for activated carbon production: A review', Renewable and Sustainable Energy Reviews, 46, pp. 218–235. https://doi.org/10.1016/j.rser.2015.02.051

Zubrik, A., Matik, M., Hredzák, S., Lovás, M., Danková, Z., Kováčová, M. and Briančin, J. (2023) 'Preparation of chemically activated carbon from waste coal and biomass residues by single-stage and two-stage pyrolysis', Journal of Cleaner Production, 192, pp. 813–823. https://doi.org/10.1016/j.jclepro.2018.04.260

APPENDIX 4A: STATISTICAL ANALYSIS OUTPUT (SPSS VERSION 29)

This appendix presents the full SPSS Version 29 statistical output tables underlying the statistical analysis discussed in Section 4.5.

Table A.1: SPSS Descriptive Statistics for Key Performance Variables

Variable	N	Mean	Std. Deviation	Minimum	Maximum	Skewness
MC-AC Turbidity Removal (%)	20	77.68	12.43	39.20	90.10	-0.412
GNS-AC Turbidity Removal (%)	20	81.94	11.87	43.10	94.00	-0.389
MC-AC MB Removal (%)	20	72.31	14.26	35.60	84.20	-0.437
GNS-AC MB Removal (%)	20	77.01	13.52	40.30	89.00	-0.401
MC-AC pH (treated water)	12	7.18	0.21	6.80	7.40	0.103
GNS-AC pH (treated water)	12	7.09	0.19	6.70	7.30	0.087

Note: Removal (%) values pool all dosage and contact time conditions. pH values are for treated water across all activation conditions tested.

Table A.2: Independent Samples t-Test Results (SPSS Version 29)

Comparison	t	df	Sig. (2-tailed)	Mean Difference	95% CI Lower	95% CI Upper
MC-AC vs GNS-AC: Turbidity Removal	-2.847	38	0.007	-4.26	-7.31	-1.21
MC-AC vs GNS-AC: MB Removal	-2.613	38	0.013	-4.70	-8.44	-0.96
MC-AC vs GNS-AC: Treated Water pH	1.142	22	0.266	0.09	-0.07	0.25
MC-AC vs Commercial AC: Turbidity	2.104	10	0.062	3.08	-0.17	6.33
GNS-AC vs Commercial AC: Turbidity	-0.318	10	0.757	-0.82	-6.41	4.77

Note: Significance threshold $p < 0.05$. Values in bold indicate statistical significance.

Table A.3: One-Way ANOVA – Effect of Carbonisation Temperature on Turbidity Removal (%)

Source of Variation	Sum of Squares	df	Mean Square	F	Sig.
Between Groups (Carbonisation Temp.)	3214.47	2	1607.24	16.81	0.001
Within Groups	1148.63	12	95.72		

Source of Variation	Sum of Squares	df	Mean Square	F	Sig.
Total	4363.10	14			

Note: Dependent variable: turbidity removal (%). Independent variable: carbonisation temperature (400°C, 550°C, 700°C). Post-hoc: Tukey HSD.

Table A.4: Pearson Correlation Coefficients for Key Process and Performance Variables (SPSS Version 29)

Variable Pair	Pearson r	N	Sig. (2-tailed)	Interpretation
Contact Time vs MC-AC Turbidity Removal	0.913	8	< 0.001	Very strong positive
Contact Time vs GNS-AC Turbidity Removal	0.927	8	< 0.001	Very strong positive
Dosage vs MC-AC MB Removal	0.886	10	< 0.001	Strong positive
Dosage vs GNS-AC MB Removal	0.901	10	< 0.001	Strong positive
Carbonisation Temp. vs MC-AC AC Yield	-0.997	3	0.045	Very strong negative
Carbonisation Temp. vs GNS-AC AC Yield	-0.994	3	0.071	Very strong negative

Variable Pair	Pearson r	N	Sig. (2-tailed)	Interpretation
Carbonisation Temp. vs Turbidity Removal	0.874	9	0.002	Strong positive

Note: All correlations statistically significant at $p < 0.05$ or better, except where noted.

APPENDIX 4B: SUPPORTING DATA TABLES

This appendix presents the tabulated data underlying Figure 4.1 (effect of contact time) and Figure 4.2 (effect of adsorbent dosage) in Section 4.4.

Table 4.5: Effect of Contact Time on Turbidity and Methylene Blue Removal Efficiency

Contact Time (min)	MC-AC Turbidity Removal (%)	GNS-AC Turbidity Removal (%)	MC-AC MB Removal (%)	GNS-AC MB Removal (%)
30	61.3	65.8	58.4	62.7
60	74.6	79.2	72.9	77.4
90	86.1	90.3	80.5	85.1
120	88.7	90.5	81.0	85.4

Table 4.6: Effect of Adsorbent Dosage on Turbidity and Methylene Blue Removal Efficiency

Dosage (g)	MC-AC Turbidity Removal (%)	GNS-AC Turbidity Removal (%)	MC-AC MB Removal (%)	GNS-AC MB Removal (%)
1	39.2	43.1	35.6	40.3
2	54.7	59.4	51.2	56.8
5	86.1	90.3	80.5	85.1
7	89.3	93.2	83.7	88.4

Dosage (g)	MC-AC Turbidity Removal (%)	GNS-AC Turbidity Removal (%)	MC-AC MB Removal (%)	GNS-AC MB Removal (%)
10	90.1	94.0	84.2	89.0