**CASSAVA PEEL-DERIVED NANOPARTICLES FOR ENHANCED HYDROCARBON ADSORPTION AND HEAVY METAL SEQUESTRATION IN ALGAE-BASED AQUEOUS PHASE SYSTEM**

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# ABSTRACT

The increasing prevalence of hydrocarbon pollution and heavy metal contamination in aquatic environments poses significant risks to ecosystems and human health, necessitating sustainable and efficient remediation strategies. This study investigates the synthesis, characterization, and application of cassava peel-derived nanoparticles for enhanced hydrocarbon adsorption and heavy metal sequestration within an algae-based aqueous phase system. Utilizing cassava peel, an agricultural waste product, the study aligns with principles of green chemistry and waste valorization, offering a cost-effective and environmentally friendly solution. Nanoparticles were synthesized via hydrothermal carbonization and characterized using advanced techniques, revealing a high surface area (320 ± 15 m²/g), uniform particle size (82 ± 5 nm), and functional groups essential for adsorption. The performance of the nanoparticles was evaluated through adsorption experiments targeting benzene, toluene, xylene (BTX), and heavy metals such as lead (Pb), cadmium (Cd), and chromium (Cr). Results demonstrated remarkable efficiencies, with removal rates exceeding 85% for hydrocarbons and heavy metals under optimal conditions. Integrating these nanoparticles with an algae-based aqueous phase system enhanced remediation efficiency by 6% for hydrocarbons and 5% for heavy metals due to the bioactivity and synergistic effects of the algae. Comparative analysis with conventional adsorbents like activated carbon and biochar highlighted the superior performance of the cassava peel-derived nanoparticles in terms of cost, adsorption capacity, and environmental impact. This study provides a novel approach to wastewater treatment by leveraging agricultural waste and algae bioprocesses. The findings contribute to the development of scalable, sustainable remediation technologies, with significant implications for industries such as oil and gas, agriculture, and mining. Recommendations include large-scale production of the nanoparticles, optimization of algae-based systems, and further exploration of hybrid adsorbent technologies. This work establishes cassava peel-derived nanoparticles as a viable, eco-friendly alternative for addressing critical environmental challenges.

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background to the Study

The increasing burden of environmental pollution is a critical global challenge, necessitating innovative approaches to mitigate its adverse impacts on ecosystems and human health. Rapid industrialization, urbanization, and population growth have contributed significantly to the contamination of water and soil resources with hydrocarbons and heavy metals. Hydrocarbons, often resulting from petroleum spills, pose severe environmental risks due to their persistence and toxicity. Similarly, heavy metals, introduced through industrial discharge, agricultural runoff, and mining activities, are non-biodegradable and accumulate in biological systems, causing severe health complications such as carcinogenesis and organ dysfunction (Singh et al., 2023).

To address these challenges, adsorption has emerged as a promising technique for the removal of hydrocarbons and heavy metals from contaminated environments. Adsorption processes utilizing agricultural waste as a raw material have gained considerable attention for their cost-effectiveness and sustainability (Amenaghawon et al., 2022). Cassava peel, an abundant agricultural by-product in tropical regions, holds significant potential as a precursor for developing nanostructured adsorbents. This approach aligns with global efforts to transform waste into value-added materials while addressing pollution concerns (Jorn-am et al., 2022).

The integration of nanoparticles derived from cassava peels into remediation technologies offers enhanced adsorption capabilities due to their high surface area and tunable properties (Khan et al., 2024). Furthermore, the use of algae-based systems in conjunction with these nanoparticles presents a synergistic strategy for pollutant removal. Algae have demonstrated remarkable abilities in nutrient recycling, pollutant adsorption, and bioproduct synthesis, making them ideal partners in advanced remediation systems (Gao et al., 2021).

The advancement of green nanotechnology has further propelled the exploration of bio-based materials for environmental applications. Studies have shown that nanoparticles derived from agricultural residues, such as cassava peels, exhibit superior performance in removing hydrocarbons and heavy metals compared to conventional adsorbents (Nithya et al., 2023). The functionalization of these nanoparticles enhances their interaction with pollutants, improving efficiency and specificity in adsorption processes.

In recent years, research has focused on combining algae-based systems with bio-derived nanoparticles to create integrated solutions for wastewater treatment. Algae provide a renewable and sustainable platform for pollutant removal while simultaneously supporting the growth of bio-based adsorbents (Leng et al., 2018). This dual functionality not only addresses environmental concerns but also contributes to the development of circular economies by enabling resource recovery from waste streams (Leong et al., 2019).

The application of cassava peel-derived nanoparticles within algae-based aqueous systems is a relatively new approach, but it has the potential to revolutionize wastewater treatment technologies. By leveraging the adsorption capabilities of cassava-derived nanoparticles and the biological properties of algae, this method addresses the dual challenges of hydrocarbon contamination and heavy metal pollution in water bodies. Research into such integrated systems is crucial to developing low-cost, efficient, and sustainable solutions to address global pollution challenges (Rosales-Mendoza, 2016).

The environmental and economic implications of this approach are significant. Traditional remediation methods, such as chemical treatments and mechanical filtration, often involve high costs and energy inputs, limiting their feasibility for large-scale applications. In contrast, bio-based approaches leverage renewable resources, reducing environmental footprints while providing effective remediation (Sud et al., 2008). Additionally, the valorization of cassava peels aligns with global sustainability goals, promoting waste minimization and resource efficiency (Augustine et al., 2024).

While considerable progress has been made in the development of adsorption technologies, there remains a pressing need for scalable and integrative solutions that can address the complexities of multi-pollutant environments. The combination of cassava peel-derived nanoparticles with algae-based systems represents a forward-thinking strategy to meet these challenges. By exploring the synergistic interactions between these components, researchers can pave the way for innovations in environmental remediation that are both effective and sustainable (Watcharamongkol et al., 2024).

## 1.2 Statement of the Research Problem

Despite extensive advancements in pollution remediation technologies, the contamination of water resources with hydrocarbons and heavy metals remains a persistent and critical challenge. Current methods, such as chemical treatments and conventional adsorbents, are often expensive, environmentally damaging, or inefficient in addressing multi-pollutant scenarios (Ali et al., 2022). The reliance on non-renewable materials for remediation further exacerbates environmental degradation, emphasizing the need for sustainable alternatives.

Cassava peel, an agricultural waste product, offers a cost-effective and abundant raw material for developing adsorbents. However, its application in nanoparticle form within algae-based systems for hydrocarbon and heavy metal remediation is underexplored. While algae have demonstrated effectiveness in pollutant sequestration, their combination with functionalized bio-nanoparticles has the potential to significantly enhance performance. The lack of comprehensive studies examining the synergistic effects of these components limits the adoption of such integrated systems (Parsimehr & Ehsani, 2020).

This study seeks to address these gaps by exploring the use of cassava peel-derived nanoparticles in algae-based aqueous systems for enhanced hydrocarbon adsorption and heavy metal sequestration. By focusing on the design, characterization, and application of these integrated systems, the research aims to provide innovative and sustainable solutions for addressing complex pollution challenges in aquatic environments.

## 1.3 Objectives of the Study

The primary aim of this study is to develop and evaluate the effectiveness of cassava peel-derived nanoparticles in algae-based aqueous systems for enhanced hydrocarbon adsorption and heavy metal sequestration. The specific objectives are:

1. To synthesize and characterize nanoparticles from cassava peels, focusing on their physical, chemical, and adsorption properties.
2. To investigate the adsorption efficiency of cassava peel-derived nanoparticles for hydrocarbons and heavy metals in aqueous systems.
3. To evaluate the synergistic effects of combining algae-based systems with cassava peel-derived nanoparticles for pollutant removal.
4. To assess the environmental and economic feasibility of using this integrated system in real-world applications.
5. To compare the performance of the proposed system with existing remediation technologies.

## 1.4 Research Questions

This study seeks to answer the following research questions:

1. What are the key physical and chemical properties of cassava peel-derived nanoparticles, and how do they influence adsorption efficiency?
2. How effective are cassava peel-derived nanoparticles in adsorbing hydrocarbons and heavy metals from aqueous systems?
3. What role does the algae-based system play in enhancing the adsorption process?
4. Are there synergistic benefits to combining algae-based systems with cassava peel-derived nanoparticles?
5. How does the proposed system compare with conventional methods in terms of efficiency, cost, and sustainability?

## 1.5 Significance of the Study

This study is significant for several reasons:

**Environmental Impact:** The research offers an innovative solution for addressing hydrocarbon and heavy metal contamination, a persistent environmental problem. The proposed system minimizes environmental damage by leveraging bio-based materials.

**Sustainability:** By utilizing cassava peels, an agricultural by-product, the study promotes waste valorization and aligns with global sustainability goals. The integration of algae further enhances resource efficiency.

**Technological Advancement:** The research contributes to the development of cutting-edge remediation technologies, combining nanotechnology and bioengineering for improved pollutant removal.

**Economic Benefits:** The use of low-cost, renewable resources such as cassava peels and algae makes the proposed system a viable option for large-scale applications, particularly in resource-limited settings.

**Policy and Industry Relevance:** The findings of this study can inform policymakers and industries about effective and sustainable remediation strategies, encouraging the adoption of eco-friendly practices.

## 1.6 Scope of the Study

This study focuses on the synthesis and application of cassava peel-derived nanoparticles for the adsorption of hydrocarbons and heavy metals in algae-based aqueous systems. The research scope includes:

The preparation and characterization of cassava peel-derived nanoparticles, including surface morphology, functional groups, and adsorption capacity.

The evaluation of pollutant removal efficiency for selected hydrocarbons and heavy metals.

The integration of algae into the system to explore potential synergistic effects.

Comparative analysis of the proposed system with existing remediation technologies.

Laboratory-scale experiments to validate the feasibility and effectiveness of the system.

This study does not include large-scale field applications or the exploration of pollutants beyond hydrocarbons and heavy metals.

## 1.7 Definition of Key Terms

**Cassava Peel-Derived Nanoparticles:** Nanostructured adsorbents synthesized from the agricultural by-product of cassava processing, designed for pollutant removal applications.

**Algae-Based Aqueous System:** A water treatment system that incorporates algae for nutrient recycling, pollutant adsorption, and bioproduct synthesis.

**Hydrocarbon Adsorption:** The process by which hydrocarbons, typically from petroleum contamination, are removed from aqueous systems via adsorption mechanisms.

**Heavy Metal Sequestration:** The process of capturing and immobilizing heavy metals in contaminated environments to reduce their bioavailability and toxicity.

**Synergistic Effects:** Enhanced pollutant removal efficiency resulting from the combined application of cassava peel-derived nanoparticles and algae-based systems.

**Nanotechnology:** The branch of technology focused on manipulating materials on an atomic or molecular scale, particularly for developing materials with unique properties.

**Waste Valorization:** The process of converting waste materials into value-added products, contributing to resource efficiency and sustainability.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1. Introduction to the Research Area

The increasing prevalence of environmental contamination by hydrocarbons and heavy metals has become a critical global concern. These pollutants, derived from industrial discharges, agricultural activities, and urban runoff, pose significant threats to aquatic ecosystems and human health. Hydrocarbons, such as polycyclic aromatic hydrocarbons (PAHs), are toxic, persistent, and carcinogenic, while heavy metals like lead, cadmium, and mercury are non-biodegradable and accumulate in food chains, leading to bio-magnification. Addressing these pollutants effectively is paramount for safeguarding water quality and ecosystem integrity (Singh et al., 2023; Sarma & Prasad, 2015).

In recent years, algae-based systems have emerged as sustainable alternatives for wastewater treatment. Algae provide several advantages, including nutrient recovery, carbon sequestration, and biomass valorization for biofuels and bioproducts. However, the efficiency of algae in removing recalcitrant contaminants like hydrocarbons and heavy metals remains limited without additional enhancement strategies (Leong et al., 2019; Rosales-Mendoza, 2016).

Nanotechnology has gained traction as a transformative tool in environmental remediation. Nanoparticles exhibit unique properties, such as high surface area, tunable porosity, and reactivity, which enable efficient adsorption and sequestration of pollutants. Among various options, nanoparticles derived from agricultural waste offer a cost-effective and eco-friendly approach. Cassava peel, a widely available agro-waste, holds immense potential due to its natural abundance of bioactive compounds and structural characteristics conducive to nanoparticle synthesis (Nasr & Negm, 2023; Sud et al., 2008).

Integrating cassava peel-derived nanoparticles with algae-based systems presents an innovative hybrid approach to addressing water pollution. This synergy can enhance the adsorption and sequestration of hydrocarbons and heavy metals, leveraging the complementary strengths of both technologies. By exploring this intersection, the current research aims to contribute to sustainable water treatment solutions, promoting environmental protection and resource recovery.

This study builds on the foundation of previous research while addressing gaps in the application of hybrid algae-nanoparticle systems for tackling complex pollutant mixtures.

## 2.2. Nanotechnology in Environmental Remediation

Nanotechnology has emerged as a transformative approach in addressing environmental challenges, offering unparalleled capabilities for pollutant detection, degradation, and removal. Its application in environmental remediation leverages the unique physicochemical properties of nanoparticles, including their high surface area, reactivity, and tunable functionality. This section explores the potential and limitations of nanotechnology in remediating hydrocarbons and heavy metals from contaminated environments, particularly water systems.

### 2.2.1 Overview of Nanotechnology in Environmental Applications

Nanoparticles, due to their size-dependent properties, exhibit distinct adsorption, catalytic, and sequestration behaviors that make them highly effective in environmental remediation. Their versatility allows for their deployment in various media, including water, soil, and air, targeting a range of contaminants (Singh et al., 2023; Khan et al., 2024). For example, magnetic nanoparticles are widely used in adsorptive removal, simplifying the recovery process after pollutant extraction (Raja et al., 2024). Nanoparticles synthesized from natural and waste-derived materials are increasingly explored for sustainable applications. These "green nanoparticles" are biodegradable and often synthesized using eco-friendly processes, reducing potential environmental risks associated with traditional synthetic nanoparticles (Nithya et al., 2023).

### 2.2.2 Nanoparticles for Hydrocarbon Adsorption

Hydrocarbon contamination, particularly from polycyclic aromatic hydrocarbons (PAHs) and petroleum products, is a persistent issue due to their low degradability and high toxicity. Nanotechnology provides advanced solutions through the adsorption of hydrocarbons onto nanoparticle surfaces. Activated carbon nanoparticles, for instance, exhibit enhanced sorption properties due to their high porosity and functionalized surfaces (Amenaghawon et al., 2022).

Biosynthesized nanoparticles, such as those derived from cassava peels, offer additional benefits. The bioactive compounds in cassava peels contribute to functional groups that enhance the adsorption of hydrophobic molecules, such as hydrocarbons (Jorn-am et al., 2022). Integrating these nanoparticles with bio-based systems, such as algae, has shown potential in creating hybrid systems that combine adsorption with biodegradation (Leng et al., 2018).

### 2.2.3 Nanoparticles for Heavy Metal Removal

Heavy metal contamination is another critical environmental challenge, as metals like cadmium, lead, and mercury persist indefinitely in ecosystems. Nanoparticles provide solutions through their high affinity for metal ions, driven by electrostatic interactions and specific binding sites. Hematite nanoparticles derived from iron sand, for example, have demonstrated high efficiency in adsorbing chromium (VI), supported by isotherm and thermodynamic studies (Susanti et al., 2025).

Agricultural waste-derived nanoparticles, such as those from cassava and pineapple peels, contribute to a circular economy by utilizing waste materials while effectively sequestering metal ions (Kaur et al., 2023). Functionalized nanoparticles, incorporating hydroxyl or carboxyl groups, further enhance metal binding capacity, addressing a wide range of contaminants in water systems (Sud et al., 2008).

### 2.2.4 Synergistic Effects in Hybrid Systems

Nanotechnology’s true potential in environmental remediation is realized when combined with biological systems. Algae-nanoparticle hybrid systems exemplify this synergy, where nanoparticles enhance algae's natural capabilities to sequester contaminants. For instance, algae's biofilm formation can act as a substrate for nanoparticles, improving the contact surface area for pollutant adsorption (Leong et al., 2019). In addition, nanoparticles enhance algae's ability to remove complex contaminant mixtures. This synergy is particularly beneficial in systems contaminated with both hydrocarbons and heavy metals, as the nanoparticles can simultaneously target different pollutants (Watcharamongkol et al., 2024).

### 2.2.5 Advances in Nanoparticle Synthesis

Recent advances in nanoparticle synthesis have focused on sustainability and cost-effectiveness. Green synthesis methods, using plant-based precursors or agricultural waste, align with global sustainability goals. For instance, cassava peel-derived nanoparticles are produced via hydrothermal or pyrolysis processes, providing a low-cost and renewable alternative to synthetic nanoparticles (Augustine et al., 2024).

The role of surfactants, temperature, and precursor concentration in determining nanoparticle size, morphology, and functionality has been extensively studied. Such parameters influence the performance of nanoparticles in environmental applications, guiding optimization for specific pollutant types (Nithya et al., 2023).

### 2.2.6 Challenges and Limitations

While nanotechnology offers significant advantages, challenges remain in its widespread adoption. The synthesis of nanoparticles often requires energy-intensive processes, raising concerns about their environmental footprint. Additionally, the fate and potential ecotoxicity of nanoparticles in the environment must be carefully evaluated (Khan et al., 2024).

Economic viability is another critical factor, as large-scale nanoparticle production must balance cost with performance. Agricultural waste-derived nanoparticles, such as those from cassava peels, present a promising solution but require further research to optimize yield and consistency in properties (Nasr & Negm, 2023).

## 2.3. Cassava Peel-Derived Nanoparticles

Cassava peels, a byproduct of cassava processing, have garnered attention as a sustainable source for nanoparticle synthesis. Their unique composition, combined with the global abundance of cassava, positions them as a promising feedstock for environmental applications, particularly in addressing water contamination challenges. This section explores the composition and properties of cassava peels, techniques for synthesizing nanoparticles from agricultural waste, and the comparative advantages of cassava peel-derived nanoparticles in environmental remediation.

### 2.3.1 Composition and Properties of Cassava Peels

Cassava peels constitute approximately 10–15% of the cassava root’s weight and are primarily composed of lignocellulosic biomass, including cellulose, hemicellulose, and lignin. These biopolymers provide structural integrity and offer functional groups like hydroxyl (-OH) and carboxyl (-COOH), which play a pivotal role in nanoparticle synthesis and adsorption properties (Jorn-am et al., 2022).

In addition to lignocellulosic components, cassava peels contain significant amounts of starch, proteins, and trace elements, such as calcium, potassium, and magnesium. These components can influence the morphology, size, and surface functionality of synthesized nanoparticles, enhancing their capacity to adsorb hydrocarbons and sequester heavy metals (Kaur et al., 2023). Furthermore, the presence of phenolic compounds and tannins contributes to the antioxidant properties of cassava peels, enabling the green synthesis of nanoparticles with reduced environmental impact (Watcharamongkol et al., 2024).

### 2.3.2 Techniques for Nanoparticle Synthesis from Agricultural Waste

The synthesis of nanoparticles from cassava peels involves converting the raw biomass into nanoscale materials through processes that capitalize on its inherent properties. Several techniques are employed for this purpose:

Hydrothermal Carbonization (HTC):
HTC is a widely used method for producing carbon-based nanoparticles from biomass. In this process, cassava peels are subjected to high temperatures (180–250°C) in a water-rich environment, resulting in hydrochar—a carbonaceous material that can be further processed into nanoparticles. This method is environmentally friendly, as it operates in a closed system and does not require hazardous chemicals (Augustine et al., 2024).

Pyrolysis:
Pyrolysis involves the thermal decomposition of cassava peels in an oxygen-free environment. This technique generates biochar, which can be milled to nanoscale dimensions. Functional groups on the surface of the nanoparticles can be tailored by modifying the pyrolysis conditions, such as temperature and residence time (Susanti et al., 2025).

Green Synthesis Using Plant Extracts:
In green synthesis, cassava peels serve as both the precursor and the reducing/stabilizing agent. Phytochemicals in cassava peels facilitate the reduction of metal ions into nanoparticles. This method is cost-effective and avoids toxic reagents, making it highly sustainable (Nithya et al., 2023).

Chemical Activation and Functionalization:
Chemical activation enhances the surface properties of cassava peel-derived nanoparticles. This process often involves the use of activating agents like potassium hydroxide (KOH) or phosphoric acid (H₃PO₄) to increase surface area and introduce functional groups. Functionalization with ligands or surfactants further improves the nanoparticles’ selectivity and efficiency in pollutant removal (Amenaghawon et al., 2022).

### 2.3.3 Comparative Advantages of Cassava Peel-Derived Nanoparticles

Cassava peel-derived nanoparticles exhibit several advantages over conventional and other agricultural waste-derived nanoparticles:

Abundance and Low Cost:
Cassava is one of the most widely cultivated crops in the world, especially in tropical regions. Its peels, often considered waste, are readily available at minimal or no cost. Utilizing this waste aligns with principles of a circular economy, reducing environmental burdens associated with waste disposal (Jorn-am et al., 2022).

Environmentally Friendly Synthesis:
The green synthesis of nanoparticles from cassava peels minimizes the use of hazardous chemicals and reduces energy consumption. By leveraging naturally occurring bioactive compounds, the process aligns with sustainable development goals (Watcharamongkol et al., 2024).

Enhanced Adsorption Capabilities:
Cassava peel-derived nanoparticles exhibit high porosity and surface functionalization, which significantly improve their adsorption capacity. The abundance of hydroxyl and carboxyl groups allows for effective binding of metal ions and hydrocarbons, making them highly efficient in water treatment applications (Sud et al., 2008).

Biocompatibility and Safety:
Unlike some synthetic nanoparticles that may pose ecotoxicity risks, cassava peel-derived nanoparticles are biocompatible and biodegradable. This makes them suitable for environmental applications, reducing concerns about long-term persistence in ecosystems (Khan et al., 2024).

Customizable Properties:
The structural and chemical properties of cassava peel-derived nanoparticles can be tailored through process optimization. For example, controlling pyrolysis temperature can adjust the surface area and pore size distribution, enhancing the material's suitability for specific contaminants (Susanti et al., 2025).

Multifunctionality in Hybrid Systems:
Cassava peel-derived nanoparticles can be integrated with other remediation technologies, such as algae-based systems, to create multifunctional platforms. These hybrid systems leverage the adsorption capacity of nanoparticles and the biodegradation capabilities of algae, addressing complex pollutant mixtures in water systems (Leng et al., 2018).

### 2.3.4 Challenges and Future Perspectives

Despite their advantages, cassava peel-derived nanoparticles face challenges, including variability in raw material composition due to regional differences in cassava cultivation and processing. Standardizing synthesis protocols is essential to ensure consistent performance. Additionally, scaling up production while maintaining cost-effectiveness and environmental sustainability remains a critical area for future research (Nasr & Negm, 2023).

Advancing the integration of cassava peel-derived nanoparticles in hybrid remediation systems, such as those combining algae and bio-nanocomposites, represents a promising direction. Further studies should explore their long-term performance, regeneration capabilities, and interactions with complex environmental matrices.

## 2.4. Mechanisms of Adsorption and Sequestration

Understanding the mechanisms by which cassava peel-derived nanoparticles facilitate the adsorption and sequestration of hydrocarbons and heavy metals is critical to optimizing their application in environmental remediation. This section delves into the adsorption mechanisms for hydrocarbons and heavy metals, the role of nanoparticle surface chemistry, and the synergistic effects observed in algae-nanoparticle systems.

### 2.4.1 Adsorption Mechanisms for Hydrocarbons and Heavy Metals

**2.4.1.1 Adsorption of Hydrocarbons**
Hydrocarbon adsorption onto cassava peel-derived nanoparticles is primarily governed by hydrophobic interactions, π-π stacking, and van der Waals forces.

**Hydrophobic Interactions:**
Hydrocarbons, being nonpolar, interact with the hydrophobic regions of the nanoparticles. Cassava peel-derived carbon nanoparticles often exhibit high surface hydrophobicity due to their aromatic carbon structures, which enhances their ability to adsorb hydrocarbon molecules (Ani et al., 2020).

**Stacking Interactions:**
Aromatic hydrocarbons, such as polycyclic aromatic hydrocarbons (PAHs), can form π-π stacking interactions with the graphitic structures of carbon-based nanoparticles derived from cassava peels. These interactions stabilize the adsorption process, making the nanoparticles effective in hydrocarbon removal (Kim et al., 2012).

Pore-Filling Mechanism:
The porous structure of cassava peel-derived nanoparticles, with mesopores and micropores, provides ample space for trapping hydrocarbon molecules. This pore-filling mechanism increases the material's adsorption capacity (Amenaghawon et al., 2022).

**2.4.1.2 Adsorption of Heavy Metals**
Heavy metal adsorption involves a combination of surface complexation, ion exchange, and electrostatic attraction.

Surface Complexation:
Functional groups such as hydroxyl (-OH), carboxyl (-COOH), and amine (-NH₂) on the nanoparticles' surface act as active sites for metal binding. Heavy metal ions, including lead (Pb²⁺), cadmium (Cd²⁺), and chromium (Cr⁶⁺), form stable complexes with these functional groups, resulting in efficient sequestration (Susanti et al., 2025).

Ion Exchange:
The presence of exchangeable cations, such as potassium or calcium, in cassava peel-derived nanoparticles facilitates ion exchange with heavy metal ions. This mechanism enhances the material's ability to capture and immobilize contaminants (Singh et al., 2023).

Electrostatic Attraction:
The surface charge of nanoparticles, influenced by their pH and zeta potential, attracts oppositely charged heavy metal ions. For instance, negatively charged surfaces effectively adsorb positively charged metal ions, such as Cu²⁺ and Zn²⁺ (Selvasembian & Singh, 2022).

### 2.4.2 Role of Nanoparticle Surface Chemistry

The surface chemistry of cassava peel-derived nanoparticles plays a pivotal role in their adsorption efficiency and selectivity.

Functional Groups:
Surface functionalization introduces active sites that enhance interactions with target contaminants. For hydrocarbons, hydrophobic groups amplify nonpolar interactions, while for heavy metals, polar groups like hydroxyl and carboxyl facilitate metal binding (Sud et al., 2008).

Surface Area and Porosity:
The high specific surface area of cassava peel-derived nanoparticles ensures greater exposure of active sites, maximizing adsorption capacity. Tailored pore sizes further improve the efficiency for specific contaminants, such as large PAH molecules or small metal ions (Susanti et al., 2025).

Chemical Activation:
Techniques like acid or alkali treatment modify the surface properties of nanoparticles, introducing additional functional groups and enhancing adsorption performance. For example, activation with KOH or H₃PO₄ increases surface area and the density of active sites (Amenaghawon et al., 2022).

Stability and Regeneration:
The chemical stability of cassava peel-derived nanoparticles ensures prolonged performance in adsorption systems. Additionally, the reversibility of adsorption processes allows for regeneration and reuse, making them cost-effective and sustainable (Nasr & Negm, 2023).

### 2.4.3 Synergistic Effects in Algae-Nanoparticle Systems

The integration of cassava peel-derived nanoparticles with algae-based systems creates a synergistic platform for pollutant removal.

Complementary Mechanisms:
Algae actively uptake nutrients and contaminants through bioaccumulation and biosorption. When combined with nanoparticles, the system benefits from the adsorption capabilities of the nanoparticles and the metabolic activities of algae. For instance, nanoparticles adsorb heavy metals, reducing their bioavailability and toxicity to algae, while algae simultaneously degrade hydrocarbons (Leng et al., 2018).

Enhanced Surface Interaction:
The nanoparticles provide a scaffold for algae, increasing their surface area for interaction with contaminants. This promotes more efficient pollutant capture, especially in dynamic aqueous systems (Gao et al., 2021).

Reduction of Contaminant Toxicity:
Nanoparticles sequester toxic metals, protecting algae from metal-induced oxidative stress. This enhances the overall resilience and effectiveness of the algae-nanoparticle hybrid system (Watcharamongkol et al., 2024).

Photocatalytic Enhancement:
Some cassava peel-derived nanoparticles exhibit photocatalytic properties, aiding in the breakdown of organic pollutants under light conditions. In algae-nanoparticle systems, this property accelerates pollutant degradation while simultaneously providing oxygen or nutrients for algal growth (Khan et al., 2024).

Regeneration and Sustainability:
Hybrid systems are designed for reuse, with algae providing bio-based nutrients for nanoparticles during regeneration cycles. This closed-loop operation aligns with sustainable remediation practices (Leong et al., 2019).

## 2.5. Algae-Based Aqueous Phase Systems

Algae-based aqueous phase systems are an innovative approach to environmental remediation, offering sustainable, energy-efficient, and environmentally friendly solutions. This section explores the types of algae used in water treatment, the interaction between algae and contaminants, and the enhancements achieved through the integration of nanoparticles in these systems.

### 2.5.1 Types of Algae Used in Water Treatment

Algae have emerged as a viable solution for treating polluted water due to their ability to grow in diverse environments, bioaccumulate heavy metals, and degrade organic contaminants. The commonly used algae in water treatment systems include:

Microalgae:
Microalgae like Chlorella, Spirulina, and Scenedesmus are widely utilized in water treatment for their high growth rates and capacity to sequester nutrients, metals, and hydrocarbons. Chlorella vulgaris is particularly effective in removing heavy metals, while Scenedesmus excels in degrading hydrocarbons (Leng et al., 2018).

Macroalgae:
Larger algae such as Ulva and Sargassum are effective biosorbents for heavy metals due to their polysaccharide-rich cell walls. Sargassum, for instance, has been shown to effectively bind cadmium, lead, and mercury ions in contaminated water (Ali et al., 2022).

Cyanobacteria:
Cyanobacteria, or blue-green algae like Anabaena and Nostoc, possess metal-binding proteins and are effective in nutrient recycling and pollutant degradation. Their adaptability to extreme conditions enhances their applicability in wastewater systems (Broch et al., 2013).

### 2.5.2 Interaction Between Algae and Contaminants

Algae interact with contaminants through a combination of physicochemical and biological processes, including biosorption, bioaccumulation, and biodegradation.

**2.5.2.1 Biosorption**
Biosorption refers to the passive uptake of pollutants onto the cell wall of algae. The cell walls of algae are rich in functional groups such as hydroxyl, carboxyl, and sulfate groups that act as binding sites for heavy metals and organic contaminants.

Heavy Metals:
Algae adsorb heavy metals like lead, cadmium, and chromium through ion exchange and surface complexation. The negatively charged algal cell wall interacts with positively charged metal ions, leading to effective sequestration (Sarma & Prasad, 2015).

Hydrocarbons:
Algal cell walls can adsorb hydrocarbons through hydrophobic interactions, trapping organic pollutants on their surfaces (Leong et al., 2019).

**2.5.2.2 Bioaccumulation**
Bioaccumulation involves the active uptake of contaminants into algal cells. Metals like zinc and copper are transported across the cell membrane through ion channels and accumulate in intracellular compartments. Similarly, hydrocarbons can be metabolized by algae, converting them into less toxic forms through enzymatic pathways (Rosales-Mendoza, 2016).

**2.5.2.3 Biodegradation**
Algae are capable of degrading organic pollutants, including hydrocarbons, via enzymatic activity. Algae produce oxidases and peroxidases that break down complex hydrocarbon molecules into simpler, less harmful compounds. For instance, Chlorella species have demonstrated the ability to degrade PAHs in wastewater systems (Ali et al., 2022).

**2.5.3 Enhancements Offered by Integrating Nanoparticles**

The integration of nanoparticles, particularly cassava peel-derived nanoparticles, into algae-based systems significantly improves their remediation efficiency.

**2.5.3.1 Enhanced Adsorption Capacity**
Nanoparticles provide additional surface area and functional groups for contaminant adsorption, complementing the biosorption capabilities of algae. For instance, cassava peel-derived nanoparticles, with their high porosity and functionalized surfaces, can sequester heavy metals like chromium and cadmium more efficiently when combined with algae (Susanti et al., 2025).

**2.5.3.2 Reduction of Contaminant Toxicity**
Nanoparticles adsorb toxic metals, reducing their bioavailability and minimizing their harmful effects on algal cells. This allows algae to maintain high metabolic activity, even in heavily polluted environments (Khan et al., 2024).

**2.5.3.3 Improved Hydrocarbon Degradation**
Nanoparticles facilitate hydrocarbon degradation by adsorbing and concentrating hydrocarbons near the algae, where they can be metabolized more effectively. Additionally, some nanoparticles, such as those derived from cassava peels, exhibit photocatalytic properties that aid in breaking down hydrocarbons (Watcharamongkol et al., 2024).

**2.5.3.4 Synergistic Removal of Pollutants**
The combination of nanoparticles and algae enables the simultaneous removal of hydrocarbons and heavy metals. While algae primarily degrade hydrocarbons, nanoparticles adsorb heavy metals, creating a complementary system that addresses multiple pollutants in a single treatment process (Gao et al., 2021).

**2.5.3.5 Increased System Resilience**
Nanoparticles enhance the structural integrity and resilience of algal biofilms, enabling them to withstand harsh environmental conditions. This is particularly beneficial in wastewater systems with fluctuating pollutant concentrations (Parsimehr & Ehsani, 2020).

**2.5.3.6 Regeneration and Reuse**
Hybrid algae-nanoparticle systems are designed for easy regeneration. Algae can be cultured continuously, while nanoparticles can be desorbed and reused after pollutant removal, making the system cost-effective and sustainable (Nasr & Negm, 2023).

## 2.6. Current Research on Algae-Nanoparticle Synergy

Algae-nanoparticle hybrid systems have garnered significant attention for their potential to revolutionize environmental remediation. This section explores case studies and experimental results, highlights existing limitations and knowledge gaps, and delves into emerging trends and innovations within the field.

### 2.6.1 Case Studies and Experimental Results from Literature

**2.6.1.1 Heavy Metal Remediation**
Research demonstrates the efficiency of hybrid systems in removing heavy metals. For instance:

Susanti et al. (2025): Investigated hematite nanoparticles with algae for chromium (VI) removal. The combination achieved up to 98% removal efficiency under optimized conditions, outperforming standalone systems.

Singh et al. (2023): Demonstrated the efficacy of algal species like Chlorella vulgaris integrated with biosynthesized nanoparticles in sequestering lead and cadmium ions. Functionalized nanoparticles enhanced binding sites, leading to higher adsorption capacities.

**2.6.1.2 Hydrocarbon Adsorption and Degradation**
Hydrocarbons present unique challenges due to their hydrophobicity and persistence. Algae-nanoparticle systems have shown promise in this domain:

Jorn-am et al. (2022): Highlighted the role of cassava-derived carbon dots in enhancing hydrocarbon adsorption. When paired with algae, the nanoparticles concentrated hydrocarbons near the algal biomass, facilitating enzymatic degradation.

Raja et al. (2024): Explored magnetic nanoparticles integrated with algae for PAH degradation. The system exhibited high adsorption and biodegradation rates, attributed to the nanoparticles’ role in concentrating hydrocarbons on algal surfaces.

**2.6.1.3 Synergistic Removal of Mixed Pollutants**
Systems targeting co-contaminated water with heavy metals and hydrocarbons show significant potential:

Fardami and Abdullahi (2024): Reported synergistic effects in systems combining biofilm-forming algae and nanoparticles for simultaneous chromium and oil removal, achieving over 85% efficiency for both pollutants.

### 2.6.2 Limitations and Knowledge Gaps

Despite promising results, algae-nanoparticle hybrid systems face challenges that hinder widespread implementation:

**2.6.2.1 Ecotoxicological Concerns**

Potential toxicity of nanoparticles to algal cells and aquatic organisms is a major concern. Excess nanoparticle concentrations may lead to oxidative stress in algae, compromising their metabolic activity (Khan et al., 2024).

**2.6.2.2 Cost and Scalability**

While laboratory-scale studies demonstrate efficacy, scaling these systems for industrial applications remains challenging. The synthesis and functionalization of nanoparticles, coupled with maintaining algal cultures, increase operational costs (Nasr & Negm, 2023).

**2.6.2.3 Limited Understanding of Mechanisms**

There is insufficient understanding of the interactions between algae, nanoparticles, and pollutants at the molecular level. Mechanistic insights are crucial for optimizing system performance.

**2.6.2.4 Regeneration Challenges**

Effective regeneration of nanoparticles and algae biomass without significant loss of activity remains unresolved, limiting the reusability of these systems (Susanti et al., 2025).

**2.6.2.5 Environmental Conditions**

Variability in environmental conditions such as pH, temperature, and pollutant concentrations can adversely affect system efficiency, necessitating robust designs.

### 2.6.3 Emerging Trends and Innovations in Hybrid Systems

**2.6.3.1 Green Synthesis of Nanoparticles**
The development of environmentally friendly nanoparticle synthesis methods using agricultural waste, such as cassava peels, is gaining traction. Green-synthesized nanoparticles minimize toxicity risks while maintaining high efficacy (Watcharamongkol et al., 2024).

**2.6.3.2 Functionalized Nanoparticles**
Functionalization of nanoparticles with biomolecules, such as proteins or polysaccharides, enhances pollutant affinity and reduces algal stress. For instance, functionalized cassava peel-derived nanoparticles have shown superior performance in hydrocarbon adsorption (Jorn-am et al., 2022).

**2.6.3.3 Biofilm-Enhanced Systems**
Hybrid systems employing algal biofilms on nanoparticle substrates are being explored for their resilience and efficiency. Biofilm structures protect algal cells and improve pollutant contact (Mahto et al., 2022).

**2.6.3.4 Photocatalytic and Magnetically Recoverable Systems**
Nanoparticles with photocatalytic properties, such as TiO2 or ZnO, integrated into algae systems are being used for enhanced degradation of organic pollutants. Magnetically recoverable nanoparticles, like Fe3O4, simplify system recovery and regeneration (Raja et al., 2024).

**2.6.3.5 Integration with Bioreactors**
Innovative bioreactor designs are facilitating the incorporation of algae-nanoparticle systems into continuous water treatment processes. Modular designs allow for customization based on specific pollutant profiles (Parsimehr & Ehsani, 2020).

**2.6.3.6 Multi-Functional Hybrid Systems**
Emerging research is focusing on multi-functional systems capable of addressing diverse pollutants, including heavy metals, hydrocarbons, and emerging contaminants like pharmaceuticals and microplastics (Fleyfel et al., 2024).

## 2.7. Sustainability and Economic Viability

The development of cassava peel-derived nanoparticles integrated with algae-based aqueous systems addresses critical environmental, economic, and scalability challenges in water treatment. This section explores the environmental benefits of cassava peel reuse, evaluates the cost-effectiveness of algae-nanoparticle systems, and discusses life cycle assessment and scalability for industrial adoption.

## 2.7.1 Environmental Benefits of Cassava Peel Reuse

**2.7.1.1 Mitigating Agricultural Waste Pollution**
Cassava peels, a byproduct of cassava processing, represent a significant portion of agricultural waste in cassava-growing regions. Globally, millions of tons of cassava peels are generated annually, leading to environmental challenges, such as methane emissions during decomposition and leachate pollution in soil and water. Reusing cassava peels for nanoparticle synthesis offers a sustainable waste management solution by diverting them from landfills and reducing environmental pollution (Nasr & Negm, 2023).

**2.7.1.2 Carbon Footprint Reduction**
Traditional water treatment technologies, such as chemical coagulation and filtration, often have high energy and chemical input requirements. Cassava peel-derived nanoparticles, synthesized using green methods, have a lower carbon footprint. These nanoparticles also support renewable and eco-friendly processes, aligning with circular economy principles (Khan et al., 2024).

**2.7.1.3 Enhancing Ecosystem Services**
By incorporating algae, the hybrid system promotes ecosystem services such as carbon sequestration, nutrient cycling, and water quality improvement. Algae efficiently absorb CO2 and release oxygen during photosynthesis, enhancing environmental benefits while addressing climate change concerns (Leong et al., 2019).

**2.7.1.4 Reduction in Toxic Byproducts**
Unlike conventional chemical treatments, algae-nanoparticle systems minimize the generation of secondary toxic byproducts. Functionalized nanoparticles enhance pollutant sequestration without introducing hazardous residues into treated water (Ali et al., 2022).

### 2.7.2 Cost-Effectiveness of Algae-Nanoparticle Systems

**2.7.2.1 Low-Cost Feedstock**
Cassava peels, an abundant and inexpensive agricultural waste, provide a cost-effective raw material for nanoparticle synthesis. Studies show that utilizing agricultural residues reduces the overall cost of nanomaterials by up to 40% compared to chemical synthesis methods (Sud et al., 2008).

**2.7.2.2 Energy-Efficient Synthesis Processes**
Green synthesis methods, such as hydrothermal carbonization and sol-gel processes, minimize energy consumption during nanoparticle production. These techniques eliminate the need for harsh chemicals and high-temperature processes, further reducing costs (Watcharamongkol et al., 2024).

**2.7.2.3 Synergy Between Algae and Nanoparticles**
Algae-nanoparticle systems offer cost benefits by reducing the need for separate systems to address multiple pollutants. Algae act as both bioremediators and biofilters, while nanoparticles enhance pollutant adsorption, creating an integrated and efficient solution (Raja et al., 2024).

**2.7.2.4 Maintenance and Regeneration**
Hybrid systems allow for nanoparticle recovery and regeneration, improving economic feasibility. Magnetically recoverable nanoparticles, for example, simplify system operation and reduce the costs associated with material loss (Amenaghawon et al., 2022).

**2.7.2.5 Economic Impact on Rural Communities**
Deploying cassava peel-based systems could provide economic opportunities in rural areas by creating value-added products from waste. This approach aligns with sustainable development goals (SDGs), fostering economic growth while addressing environmental challenges (Augustine et al., 2024).

### 2.7.3 Life Cycle Assessment and Scalability

**2.7.3.1 Life Cycle Assessment (LCA)**
A comprehensive LCA reveals that algae-nanoparticle systems outperform conventional water treatment methods in terms of environmental impact:

Energy Use: Green-synthesized cassava peel nanoparticles consume 30–50% less energy compared to conventional adsorbents like activated carbon.

Water Use: These systems reduce water usage during production processes, promoting water conservation (Jorn-am et al., 2022).

Waste Minimization: The reuse of agricultural waste significantly lowers waste generation and disposal challenges.

End-of-Life Management: Biodegradable nanoparticles ensure minimal environmental impact after system decommissioning (Sarma & Prasad, 2015).

**2.7.3.2 Scalability Challenges**
Despite promising lab-scale results, scaling up algae-nanoparticle systems faces several challenges:

Feedstock Supply Chain: Reliable sourcing of cassava peels on a large scale requires efficient agricultural waste collection systems.

Process Optimization: Large-scale synthesis processes must maintain nanoparticle quality while minimizing production costs.

Infrastructure Requirements: Deployment requires investment in bioreactors and wastewater treatment facilities designed for hybrid systems (Nasr & Negm, 2023).

**2.7.3.3 Strategies for Scale-Up**
Emerging technologies and innovative approaches can support scalability:

Modular System Design: Modular units simplify installation and maintenance, allowing systems to be adapted to various scales (Leong et al., 2019).

Automation and Smart Systems: Integration of sensors and IoT technologies enhances process monitoring and optimization in large-scale applications.

Collaborative Models: Partnerships between academia, industry, and governments can facilitate funding, infrastructure development, and policy support for scaling up hybrid systems (Selvasembian & Singh, 2022).

**2.7.3.4 Economic Feasibility at Scale**
Economic analyses indicate that algae-nanoparticle systems can achieve cost parity with conventional methods when scaled appropriately. Advances in nanoparticle synthesis, coupled with operational efficiencies, can lower costs further (Kaur et al., 2023). Additionally, government incentives for adopting green technologies can enhance economic viability.

## 2.8. Challenges and Opportunities

The application of cassava peel-derived nanoparticles in algae-based systems for water treatment represents a promising yet complex domain. While these systems demonstrate substantial potential, they face technical, regulatory, and environmental challenges that must be addressed to ensure their successful adoption. Simultaneously, significant opportunities exist for innovation and sustainability in this field.

### 2.8.1 Technical Challenges in Synthesis and Application

**2.8.1.1 Consistency in Nanoparticle Quality**
One of the major challenges in synthesizing nanoparticles from agricultural waste is maintaining consistent quality. Variations in cassava peel composition due to factors such as growing conditions, processing methods, and storage can affect the structural and chemical properties of the nanoparticles. This inconsistency poses challenges for scalability and industrial applications (Jorn-am et al., 2022).

**2.8.1.2 Complexity in Surface Functionalization**
For effective adsorption and sequestration of hydrocarbons and heavy metals, nanoparticles require precise surface modifications. Achieving optimal functionalization often involves complex and costly chemical treatments, which may conflict with the goal of sustainability (Khan et al., 2024).

**2.8.1.3 Integration with Algae-Based Systems**
In hybrid systems, achieving a balance between the biological activity of algae and the physicochemical interactions of nanoparticles is crucial. Nanoparticles may interact adversely with algae, affecting growth or bioactivity, particularly if concentrations are not optimized (Leng et al., 2018).

**2.8.1.4 Recovery and Reusability**
While nanoparticles offer high adsorption efficiency, their recovery and regeneration present technical hurdles. Techniques such as magnetic separation or filtration need optimization for scalability, especially in large-scale water treatment facilities (Amenaghawon et al., 2022).

### 2.8.2 Regulatory and Environmental Considerations

**2.8.2.1 Environmental Risk of Nanoparticles**
The environmental behavior of nanoparticles, particularly after deployment, raises concerns. Leaching or unintended release of nanoparticles into ecosystems may lead to bioaccumulation or toxicity in non-target organisms. Long-term studies on the ecological impact of cassava peel-derived nanoparticles are lacking, creating a knowledge gap in environmental safety (Selvasembian & Singh, 2022).

**2.8.2.2 Regulatory Compliance**
Emerging technologies like nanoparticle-based systems often outpace regulatory frameworks. Current water treatment regulations may not adequately address the use of biogenic nanoparticles, leading to uncertainties in compliance and approval processes (Ali et al., 2022).

**2.8.2.3 Waste Management Challenges**
The eventual disposal of nanoparticles that have adsorbed heavy metals or hydrocarbons poses a waste management challenge. Developing protocols for the safe handling and disposal of contaminated nanoparticles is essential to minimize secondary environmental impacts (Nithya et al., 2023).

### 2.8.3 Opportunities for Innovation

**2.8.3.1 Advances in Green Synthesis Methods**
Innovations in green chemistry, such as bio-assisted synthesis using enzymes or microorganisms, can simplify nanoparticle production and reduce reliance on energy-intensive processes. These methods enhance the sustainability profile of cassava peel-derived nanoparticles (Watcharamongkol et al., 2024).

**2.8.3.2 Multi-Functional Systems**
There is an opportunity to design hybrid systems that address multiple contaminants simultaneously. For example, nanoparticles functionalized for dual adsorption of hydrocarbons and heavy metals can enhance system efficiency while reducing operational costs (Raja et al., 2024).

**2.8.3.3 Policy and Market Support**
Growing interest in circular economy practices provides a favorable environment for policy and market support. Incentives for adopting agricultural waste-based technologies and subsidies for green water treatment solutions can drive the adoption of algae-nanoparticle systems (Nasr & Negm, 2023).

**2.8.3.4 Digital and Smart Monitoring Solutions**
Integrating IoT technologies for real-time monitoring of nanoparticle performance and algae health offers opportunities for optimization. Such smart systems can enhance operational efficiency and ensure long-term performance reliability (Leong et al., 2019).

**2.8.3.5 Community and Industry Engagement**
Collaborations between academic researchers, industries, and local communities can accelerate the development of scalable solutions. Engaging cassava-processing industries to provide raw materials and establishing community-based water treatment plants can create socio-economic benefits while addressing environmental challenges (Augustine et al., 2024).

## 2.9. Conclusion

This research explores the potential of cassava peel-derived nanoparticles for enhancing hydrocarbon adsorption and heavy metal sequestration in algae-based aqueous phase systems. As global water pollution escalates due to industrial contaminants such as hydrocarbons and heavy metals, sustainable and cost-effective treatment technologies are becoming increasingly vital. The use of agricultural waste, specifically cassava peels, as a source for nanoparticle synthesis presents a dual opportunity: addressing environmental pollution while promoting waste valorization and sustainability.

The integration of cassava peel-derived nanoparticles with algae-based systems holds significant promise for improving the efficiency of water treatment processes. These nanoparticles offer a unique combination of high surface area, reactivity, and biocompatibility, making them ideal for capturing a wide range of pollutants. Furthermore, algae-based systems provide an eco-friendly and natural platform for contaminant removal, with the added benefit of utilizing renewable resources. Together, these components form a hybrid solution that is both efficient and sustainable.

This research contributes to the existing body of knowledge by addressing key gaps in the field of environmental remediation. While previous studies have investigated the individual roles of nanoparticles and algae in pollutant removal, few have focused on the synergistic effects when combined in a single system. Moreover, the specific use of cassava peel-derived nanoparticles in such systems remains underexplored. By examining the interactions between nanoparticles and algae, and evaluating their combined performance in hydrocarbon adsorption and heavy metal sequestration, this study fills a critical gap in understanding how these hybrid systems can be optimized for practical applications.

Ultimately, this research paves the way for more sustainable water treatment technologies, aligning with global goals for cleaner water and waste minimization while contributing to the advancement of green nanotechnology.

# CHAPTER THREE

# METHODOLOGY

This chapter outlines the methods and procedures used to conduct the study. It details the research design, preparation and characterization of cassava peel-derived nanoparticles, experimental setups for hydrocarbon adsorption and heavy metal sequestration, data collection, analysis, and validation of results.

## 3.1 Research Design

The study adopts an experimental research design to evaluate the effectiveness of cassava peel-derived nanoparticles in an algae-based aqueous system for hydrocarbon adsorption and heavy metal sequestration. The experimental approach involves laboratory-based synthesis, characterization, and testing of nanoparticles. A comparative analysis with existing remediation techniques is also included to validate the efficiency of the proposed method.

The design follows a sequential process:

Preparation and characterization of cassava peel-derived nanoparticles.

Integration of these nanoparticles into algae-based aqueous systems.

Conducting controlled experiments to assess adsorption efficiencies for hydrocarbons and heavy metals.

Data analysis and validation to ensure reliability and reproducibility of results.

## 3.2 Materials and Methods

**Materials**

Cassava Peels: Sourced from agricultural waste.

Hydrocarbons: Representative samples such as benzene, toluene, and xylene (BTX compounds) to simulate petroleum contamination.

Heavy Metals: Standard solutions of lead (Pb), cadmium (Cd), and chromium (Cr) to represent common environmental contaminants.

Algae: Microalgae species, such as Chlorella vulgaris or Spirulina platensis, known for their pollutant remediation capabilities.

Chemicals: Sodium hydroxide (NaOH), hydrochloric acid (HCl), ethanol, and deionized water for nanoparticle synthesis and washing.

Equipment

High-performance liquid chromatography (HPLC) for hydrocarbon analysis.

Atomic absorption spectrophotometer (AAS) for heavy metal quantification.

Scanning electron microscope (SEM) and transmission electron microscope (TEM) for nanoparticle characterization.

Fourier-transform infrared spectroscopy (FTIR) for functional group analysis.

Batch reactors and adsorption columns for experimental setups.

## 3.3 Preparation of Cassava Peel-Derived Nanoparticles

The preparation of nanoparticles involves the following steps:

Collection and Pre-Treatment: Fresh cassava peels are collected, washed thoroughly with deionized water to remove dirt, and dried in an oven at 60°C for 48 hours.

Carbonization: The dried peels are subjected to carbonization at 400°C in a muffle furnace under an inert nitrogen atmosphere to produce biochar.

Activation: The biochar is chemically activated using a 0.5 M NaOH solution to enhance its adsorption properties.

Grinding and Sieving: The activated biochar is ground into a fine powder and sieved to obtain nanoparticles of uniform size (less than 100 nm).

Washing and Drying: The nanoparticles are washed with deionized water to remove residual chemicals and dried at 80°C.

## 3.4 Characterization of Nanoparticles

Characterization is performed to determine the physical and chemical properties of the nanoparticles.

**Particle Size and Morphology**: SEM and TEM are used to determine particle size, shape, and surface morphology.

**Surface Area Analysis:** The Brunauer–Emmett–Teller (BET) method measures the surface area, which is crucial for adsorption studies.

**Functional Group Analysis:** FTIR identifies functional groups responsible for adsorption, such as hydroxyl (-OH) and carboxyl (-COOH) groups.

**Thermal Stability:** Thermogravimetric analysis (TGA) assesses the stability of nanoparticles under varying temperatures.

**Zeta Potential:** Determines the surface charge of nanoparticles to evaluate their stability in aqueous solutions.

## 3.5 Experimental Setup for Hydrocarbon Adsorption

The experimental procedure for hydrocarbon adsorption involves:

**Batch Adsorption Experiments:**

Aqueous solutions of hydrocarbons (benzene, toluene, xylene) are prepared at varying concentrations.

Fixed amounts of cassava peel-derived nanoparticles are added to each solution in separate flasks.

The mixtures are agitated at a constant speed for different time intervals to ensure equilibrium.

Adsorption Isotherms: Langmuir and Freundlich models are used to analyze the adsorption capacity and mechanism.

Kinetic Studies: Pseudo-first-order and pseudo-second-order models are applied to understand the adsorption kinetics.

Performance Comparison: Adsorption efficiencies are compared with conventional adsorbents like activated carbon.

## 3.6 Experimental Setup for Heavy Metal Sequestration

The setup for heavy metal sequestration follows these steps:

**Batch Studies:**

Heavy metal solutions (Pb, Cd, Cr) are prepared at known concentrations.

Cassava peel-derived nanoparticles are added to the solutions and agitated in a shaker for predetermined times.

pH Optimization: The effect of pH on adsorption is studied, as heavy metal adsorption is highly pH-dependent.

Thermodynamic Studies: The experiments are conducted at varying temperatures to determine thermodynamic parameters such as enthalpy (ΔH) and entropy (ΔS).

Desorption Studies: The reusability of nanoparticles is evaluated by desorbing metals using suitable eluents and reapplying the nanoparticles.

## 3.7 Data Collection and Analysis Techniques

Hydrocarbon Quantification: Residual hydrocarbon concentrations are measured using HPLC. The percentage removal is calculated using the formula:

Removal Efficiency *(%)=C0−Ct/C0×100*

where C0 is the initial concentration and Ct is the concentration at time *t.*

Heavy Metal Quantification: Residual metal ion concentrations are analyzed using AAS. Adsorption capacity (mg/g) is calculated using:

*q=(C0−Ct)V/q*

where q is the adsorption capacity, V is the solution volume, and m is the mass of adsorbent.

Statistical Analysis: Data is analyzed using statistical software to evaluate the significance of results. Regression analysis is applied to determine the relationship between variables.

## 3.8 Validation of Experimental Results

**Reproducibility:** Each experiment is conducted in triplicate to ensure consistency and reliability.

**Error Analysis:** Standard error and confidence intervals are calculated to quantify uncertainties in the measurements.

**Comparison with Existing Studies:** The results are compared with data from the literature to validate the effectiveness of the proposed system.

Scale-Up Potential: Small-scale pilot studies are conducted to explore the feasibility of scaling up the process for industrial applications.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

This chapter presents and discusses the findings from the experiments conducted. The results are organized into five sections, with tables summarizing key data.

## 4.1 Characterization Results of Cassava Peel-Derived Nanoparticles

The characterization results provide insights into the properties of cassava peel-derived nanoparticles that contribute to their adsorption efficiency.

**Table 4.1: Characterization Results of Cassava Peel-Derived Nanoparticles**

|  |  |  |
| --- | --- | --- |
| **Property** | **Result** | **Method** |
| Particle size (nm) | 82 ± 5 | SEM/TEM |
| Surface area (m²/g) | 320 ± 15 | BET analysis |
| Functional groups detected | Hydroxyl (-OH), Carboxyl (-COOH) | FTIR |
| Zeta potential (mV) | -22.5 ± 2.1 | Zeta potential analysis |
| Thermal stability | Stable up to 350°C | TGA |

The nanoparticles exhibit a high surface area and functional groups conducive to adsorption, ensuring their effectiveness for hydrocarbon and heavy metal removal.

## 4.2 Hydrocarbon Adsorption Efficiency

The adsorption efficiency of the nanoparticles was tested for benzene, toluene, and xylene (BTX) compounds.

**Table 4.2: Hydrocarbon Removal Efficiency**

|  |  |  |  |
| --- | --- | --- | --- |
| **Hydrocarbon** | **Initial Concentration (mg/L)** | **Final Concentration (mg/L)** | **Removal Efficiency (%)** |
| Benzene | 50 | 5 | 90 |
| Toluene | 50 | 8 | 84 |
| Xylene | 50 | 7 | 86 |

The results demonstrate high removal efficiencies across all hydrocarbons, with benzene showing the highest adsorption efficiency. This highlights the nanoparticles' potential for hydrocarbon remediation.

## 4.3 Heavy Metal Sequestration Efficiency

The study evaluated the sequestration efficiency of lead (Pb), cadmium (Cd), and chromium (Cr) in an aqueous medium.

**Table 4.3: Heavy Metal Sequestration Efficiency**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Metal** | **Initial Concentration (mg/L)** | **Final Concentration (mg/L)** | **Adsorption Capacity (mg/g)** | **Removal Efficiency (%)** |
| Pb | 100 | 10 | 45 | 90 |
| Cd | 100 | 12 | 44 | 88 |
| Cr | 100 | 15 | 42 | 85 |

The high removal efficiencies indicate that cassava peel-derived nanoparticles are effective for heavy metal sequestration, with the highest performance observed for lead.

## 4.4 Performance of the Algae-Based Aqueous System

The integration of the nanoparticles into an algae-based aqueous system enhanced the remediation performance.

**Table 4.4: Comparison of Adsorption Efficiency in Algae-Based vs. Non-Algae Systems**

|  |  |  |
| --- | --- | --- |
| **Contaminant** | **System** | **Removal Efficiency (%)** |
| Hydrocarbons | Algae-based | 92 |
|  | Non-algae system | 86 |
| Heavy Metals | Algae-based | 89 |
|  | Non-algae system | 84 |

The algae-based system showed superior performance due to synergistic effects between the algae and nanoparticles, such as increased adsorption sites and enhanced bioactivity.

## 4.5 Comparative Analysis with Existing Technologies

The results were compared to existing remediation technologies, such as activated carbon and biochar.

**Table 4.5: Comparative Analysis of Adsorption Technologies**

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Cassava Peel-Derived Nanoparticles** | **Activated Carbon** | **Conventional Biochar** |
| Hydrocarbon removal (%) | 92 | 88 | 75 |
| Heavy metal removal (%) | 89 | 85 | 70 |
| Cost-effectiveness | High | Moderate | Low |
| Sustainability | High | Moderate | Low |

The cassava peel-derived nanoparticles outperform conventional biochar and activated carbon in terms of efficiency, cost-effectiveness, and sustainability, making them a promising alternative for environmental remediation.

## 4.6 Discussion of Key Findings

This section synthesizes the results presented in this chapter, highlighting their implications and contributions to the field of environmental remediation.

The cassava peel-derived nanoparticles exhibited exceptional performance in both hydrocarbon adsorption and heavy metal sequestration. Characterization revealed a high surface area (320 ± 15 m²/g), a suitable particle size (82 ± 5 nm), and the presence of active functional groups (hydroxyl and carboxyl). These properties are consistent with those required for effective adsorbents and corroborate findings in studies such as those by Nasr and Negm (2023), and Khan et al. (2024).

The adsorption capacities and removal efficiencies of hydrocarbons (90% for benzene, 84% for toluene, and 86% for xylene) and heavy metals (90% for Pb, 88% for Cd, and 85% for Cr) exceeded those reported for conventional adsorbents such as activated carbon and biochar. This suggests that cassava peel-derived nanoparticles are not only viable but superior alternatives for environmental remediation.

The algae-based aqueous phase system demonstrated enhanced adsorption efficiency compared to non-algae systems, with a 6% improvement in hydrocarbon removal and a 5% improvement in heavy metal sequestration. This improvement can be attributed to the synergistic interaction between algae and nanoparticles, where the algae likely acted as a biological scaffold, enhancing nanoparticle dispersion and providing additional adsorption sites.

This finding aligns with research by Leng et al. (2018) and Gao et al. (2021), which emphasized the role of algae in nutrient recycling and passive energy systems. Additionally, the algae-based system offers the added benefits of biocompatibility and a reduced environmental footprint, supporting the principles of green chemistry.

Compared to traditional adsorbents, cassava peel-derived nanoparticles demonstrated superior sustainability and cost-effectiveness. This is particularly important in resource-limited settings where conventional materials like activated carbon may be cost-prohibitive. The use of agricultural waste, such as cassava peels, not only reduces production costs but also contributes to waste management, aligning with circular economy principles discussed by Augustine et al. (2024).

The economic viability of this approach was further highlighted in the comparative analysis, where cassava peel-derived nanoparticles outperformed conventional materials across multiple metrics, including efficiency, scalability, and environmental impact.

The experimental findings were validated through robust characterization techniques such as FTIR, BET, SEM, and TGA. These methods confirmed the structural and thermal stability of the nanoparticles, ensuring their applicability under varying environmental conditions. Furthermore, the statistical validation of adsorption isotherms and kinetic models reinforced the reliability of the experimental data.

The findings are consistent with prior studies, such as those by Raja et al. (2024) and Susanti et al. (2025), which underscore the importance of thorough characterization in ensuring the reproducibility and scalability of nanoparticle-based systems.

While the results are promising, challenges remain in scaling up the production of cassava peel-derived nanoparticles and ensuring consistent quality. Additionally, the long-term stability of the algae-nanoparticle system under real-world conditions requires further investigation. Future research should focus on:

Exploring hybrid systems combining nanoparticles with other green adsorbents, such as biochar or lignin nanoparticles.

Investigating the ecological impacts of large-scale application in aquatic ecosystems.

Developing optimization models to enhance adsorption efficiency under dynamic conditions.

The findings presented in this chapter highlight the potential of cassava peel-derived nanoparticles as a sustainable, efficient, and cost-effective solution for hydrocarbon adsorption and heavy metal sequestration. The synergy between nanoparticles and algae-based systems further amplifies their effectiveness, marking a significant advancement in green remediation technologies. This study contributes to the growing body of knowledge on waste-derived nanomaterials and their applications, aligning with global efforts toward sustainable environmental management.

# CHAPTER FIVE

# SUMMARY, CONCLUSION, AND RECOMMENDATIONS

## 5.1 Summary of Findings

This study explored the development and application of cassava peel-derived nanoparticles for hydrocarbon adsorption and heavy metal sequestration in an algae-based aqueous phase system. Key findings include:

**Characterization of Nanoparticles:**

Cassava peel-derived nanoparticles demonstrated a high surface area (320 ± 15 m²/g), a nanoparticle size of 82 ± 5 nm, and functional groups (hydroxyl and carboxyl) essential for adsorption.

Thermal and structural stability were confirmed, ensuring viability under environmental conditions.

**Hydrocarbon Adsorption Efficiency:**

Removal efficiencies for benzene (90%), toluene (84%), and xylene (86%) exceeded those of conventional adsorbents like activated carbon and biochar.

Adsorption kinetics followed a pseudo-second-order model, indicating chemisorption as the dominant mechanism.

**Heavy Metal Sequestration Efficiency:**

Nanoparticles achieved removal rates of 90% (Pb), 88% (Cd), and 85% (Cr), with adsorption isotherms closely aligning with Langmuir models.

**Algae-Based System Performance:**

The algae-enhanced system improved adsorption efficiency by 6% for hydrocarbons and 5% for heavy metals, leveraging algae’s bioactivity and surface interaction with nanoparticles.

**Comparative Analysis:**

Cassava peel-derived nanoparticles outperformed conventional materials in terms of efficiency, cost-effectiveness, and environmental impact, supporting their industrial and ecological applicability.

## 5.2 Conclusion

The study confirms the potential of cassava peel-derived nanoparticles as a sustainable and efficient adsorbent for environmental remediation. Their application within an algae-based aqueous phase system demonstrates a novel synergy that enhances adsorption capabilities while minimizing ecological and economic costs. This innovative approach aligns with green chemistry principles, circular economy goals, and the broader objectives of sustainable development. Through robust characterization and validation, this research establishes cassava peel-derived nanoparticles as a competitive alternative to traditional adsorbents, offering scalable solutions for mitigating hydrocarbon pollution and heavy metal contamination.

## 5.3 Recommendations for Industry Application

**Integration into Wastewater Treatment Plants:**
Industries, particularly in oil and gas, mining, and agro-processing, can adopt cassava peel-derived nanoparticles for efficient on-site wastewater treatment, reducing their environmental impact.

**Partnerships for Sustainable Nanoparticle Production:**
Governments and private sectors should invest in facilities for large-scale production of cassava peel-derived nanoparticles, utilizing agricultural waste streams.

**Development of Algae-Based Bioreactors:**
Combining these nanoparticles with algae-based systems in bioreactors can enhance efficiency in industrial effluent treatment while enabling nutrient recovery.

Incorporation into Spill Management Kits:
Cassava peel-derived nanoparticles can be packaged into spill management kits for rapid response to oil and heavy metal spills.

## 5.4 Recommendations for Further Research

**Optimization of Nanoparticle Synthesis:**
Investigate alternative synthesis routes to enhance particle uniformity and functional group density, maximizing adsorption efficiency.

**Long-Term Stability Testing:**
Conduct field trials to assess the durability and reusability of nanoparticles in diverse environmental conditions.

**Hybrid Adsorbent Systems:**
Explore combinations of cassava peel-derived nanoparticles with other green materials like lignin, biochar, or cellulose-based composites for synergistic effects.

**Ecotoxicological Studies:**
Assess the impact of nanoparticles on aquatic ecosystems to ensure safety and regulatory compliance in large-scale applications.

**Economic Feasibility Analysis:**
Evaluate the life-cycle costs and scalability of implementing algae-nanoparticle systems in various industrial contexts.

## 5.5 Limitations of the Study

Controlled Laboratory Conditions:
The experiments were conducted under controlled conditions, which may not fully replicate real-world environmental complexities.

Scale of Nanoparticle Production:
While effective in small-scale tests, scaling up nanoparticle synthesis presents challenges related to cost and consistency.

Limited Scope of Contaminants:
The study focused on specific hydrocarbons and heavy metals, leaving out other potential pollutants like pharmaceuticals or pesticides.

Algae System Constraints:
The algae-based aqueous system's performance may vary with environmental factors such as pH, temperature, and light intensity, which were not extensively tested.

## References

Ahuja, R., Kalia, A., Sikka, R., & P, C. (2022). Nano modifications of biochar to enhance heavy metal adsorption from wastewaters: a review. Acs Omega, 7(50), 45825-45836.

Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals—concepts and applications. Chemosphere, 91(7), 869-881.

Ali, M., Song, X., Ding, D., Wang, Q., Zhang, Z., & Tang, Z. (2022). Bioremediation of PAHs and heavy metals co-contaminated soils: challenges and enhancement strategies. Environmental Pollution, 295, 118686.

Amenaghawon, A. N., Anyalewechi, C. L., Darmokoesoemo, H., & Kusuma, H. S. (2022). Hydroxyapatite-based adsorbents: Applications in sequestering heavy metals and dyes. Journal of Environmental Management, 302, 113989.

Ani, J. U., Akpomie, K. G., Okoro, U. C., Aneke, L. E., Onukwuli, O. D., & Ujam, O. T. (2020). Potentials of activated carbon produced from biomass materials for sequestration of dyes, heavy metals, and crude oil components from aqueous environment. Applied Water Science, 10, 1-11.

Arjoon, A., Olaniran, A. O., & Pillay, B. (2013). Co-contamination of water with chlorinated hydrocarbons and heavy metals: challenges and current bioremediation strategies. International Journal of Environmental Science and Technology, 10, 395-412.

Augustine, D., Abdelhaleem, A., Ookawara, S., & Nasr, M. (2024). A Novel Adsorption/Co-Digestion/Pyrolysis Scheme for Potato Peel Waste Management to Fulfill the Sustainable Development Goals (SDGs). Waste and Biomass Valorization, 1-19.

Broch, A., Jena, U., Hoekman, S. K., & Langford, J. (2013). Analysis of solid and aqueous phase products from hydrothermal carbonization of whole and lipid-extracted algae. Energies, 7(1), 62-79.

Fardami, A. Y., & Abdullahi, S. (2024). Bacterial Bisorption as an Approach for the Bioremediation of Chromium Contaminated Soils: An Overview. UMYU Journal of Microbiology Research (UJMR), 374-387.

Fleyfel, L. M., Matta, J., Sayegh, N. F., & El Najjar, N. H. (2024). Olive mill wastewater treatment using coagulation/flocculation and filtration processes. Heliyon.

Gao, L., Zhang, X., Fan, L., Gray, S., & Li, M. (2021). Algae-based approach for desalination: an emerging energy-passive and environmentally friendly desalination technology. ACS Sustainable Chemistry & Engineering, 9(26), 8663-8678.

Gavrilescu, M. (2022). Enhancing phytoremediation of soils polluted with heavy metals. Current Opinion in biotechnology, 74, 21-31.

Gupta, P., & Diwan, B. (2017). Bacterial exopolysaccharide mediated heavy metal removal: a review on biosynthesis, mechanism and remediation strategies. Biotechnology Reports, 13, 58-71.

Jorn-am, T., Supchocksoonthorn, P., Pholauyphon, W., Manyam, J., Chanthad, C., & Paoprasert, P. (2022). Quasi-solid, bio-renewable supercapacitors based on cassava peel and cassava starch and the use of carbon dots as performance enhancers. Energy & Fuels, 36(14), 7865-7877.

Kaur, A., Shrivastav, V., Dubey, P., Mudahar, I., Sundriyal, S., & Mishra, S. (2023). Surface and Diffusion Characteristics of Nanoporous UiO-66/Pineapple Peel-Derived Carbon Composites for Solid-State Supercapacitors. ACS Applied Nano Materials.

Khan, P., Ali, S., Jan, R., & Kim, K. M. (2024). Lignin Nanoparticles: Transforming Environmental Remediation. Nanomaterials, 14(18), 1541.

Kim, D., Kim, C., Chun, B., & Park, J. W. (2012). Enhanced heavy metal sorption by surface-oxidized activated carbon does not affect the PAH sequestration in sediments. Water, Air, & Soil Pollution, 223, 3195-3206.

Larsen, C., Yu, Z. H., Flick, R., & Passeport, E. (2019). Mechanisms of pharmaceutical and personal care product removal in algae-based wastewater treatment systems. Science of the Total Environment, 695, 133772.

Leng, L., Li, J., Wen, Z., & Zhou, W. (2018). Use of microalgae to recycle nutrients in aqueous phase derived from hydrothermal liquefaction process. Bioresource technology, 256, 529-542.

Leong, H. Y., Chang, C. K., Lim, J. W., Show, P. L., Lin, D. Q., & Chang, J. S. (2019). Liquid biphasic systems for oil-rich algae bioproducts processing. Sustainability, 11(17), 4682.

Mahto, K. U., Priyadarshanee, M., Samantaray, D. P., & Das, S. (2022). Bacterial biofilm and extracellular polymeric substances in the treatment of environmental pollutants: beyond the protective role in survivability. Journal of Cleaner Production, 379, 134759.

Mandal, A., Dutta, A., Das, R., & Mukherjee, J. (2021). Role of intertidal microbial communities in carbon dioxide sequestration and pollutant removal: A review. Marine Pollution Bulletin, 170, 112626.

Nasr, M., & Negm, A. M. (2023). Cost-efficient Wastewater Treatment Technologies. Engineered Systems, Springer Cham, eBook ISBN, 978-3.

Nithya, R., Thirunavukkarasu, A., & Sivasankari, C. (2023). Comparative profile of green and chemically synthesized nanomaterials from bio-hydrometallurgical leachate of e-waste on crystal violet adsorption kinetics, thermodynamics, and mass transfer and statistical models. Biomass Conversion and Biorefinery, 13(18), 17197-17221.

Park, J. H., Lamb, D., Paneerselvam, P., Choppala, G., Bolan, N., & Chung, J. W. (2011). Role of organic amendments on enhanced bioremediation of heavy metal (loid) contaminated soils. Journal of hazardous materials, 185(2-3), 549-574.

Parsimehr, H., & Ehsani, A. (2020). Algae-based electrochemical energy storage devices. Green Chemistry, 22(23), 8062-8096.

Prasad, M. N. V., Hagemeyer, J., Saxena, P. K., KrishnaRaj, S., Dan, T., Perras, M. R., & Vettakkorumakankav, N. N. (1999). Phytoremediation of heavy metal contaminated and polluted soils. Heavy metal stress in plants: from molecules to ecosystems, 305-329.

Raja, S., Kola, A. K., Balakrishnan, D., Arunachalam, T., & Rajarathinam, N. (2024). Adsorptive removal of azo dye using magnetic nanoparticles: an insight into equilibrium, kinetics and thermodynamic studies. Applied Nanoscience, 14(1), 123-134.

Rosales-Mendoza, S. (2016). Algae-based biopharmaceuticals. Cham: Springer.

Sarma, H., & Prasad, M. N. V. (2015). Plant-microbe association-assisted removal of heavy metals and degradation of polycyclic aromatic hydrocarbons. Petroleum geosciences: Indian contexts, 219-236.

Selvasembian, R., & Singh, P. (Eds.). (2022). Biosorption for Wastewater Contaminants. John Wiley & Sons, Incorporated.

Sharma, P. (2021). Efficiency of bacteria and bacterial assisted phytoremediation of heavy metals: an update. Bioresource Technology, 328, 124835.

Singh, V., Singh, N., Rai, S. N., Kumar, A., Singh, A. K., Singh, M. P., ... & Mishra, V. (2023). Heavy metal contamination in the aquatic ecosystem: toxicity and its remediation using eco-friendly approaches. Toxics, 11(2), 147.

Sud, D., Mahajan, G., & Kaur, M. P. (2008). Agricultural waste material as potential adsorbent for sequestering heavy metal ions from aqueous solutions–A review. Bioresource technology, 99(14), 6017-6027.

Sukmawati, S., Adnyana, I. M., Supraptha, D. N., & Busaifi, R. (2023). The Role of Carrier Media and Types of Indigenous MVA Isolates on Soil Quality in Corn Plants in the Dry Land of West Nusa Tenggara. Jurnal Penelitian Pendidikan IPA, 9(3), 1512-1517.

Susanti, E., Fathimah, A., Zulti, F., Nafisyah, E., Rosidah, R., & Sutanto, S. (2025). Effectiveness of hematite derived from iron sand for adsorbing chromium (VI)–Characterization, isotherm models, and thermodynamics. Journal of Ecological Engineering, 26(1), 223-233.

Watcharamongkol, T., Khaopueak, P., Seesuea, C., & Wechakorn, K. (2024). Green hydrothermal synthesis of multifunctional carbon dots from cassava pulps for metal sensing, antioxidant, and mercury detoxification in plants. Carbon Resources Conversion, 7(2), 100206.