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Processing Banana Peel Waste (*Musa sapientum*) as adsorbent for Pollutant Removal from Aqueous Media: A Comprehensive Review

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ABSTRACT

This review provides a comprehensive analysis of current literature on the use of banana (*Musa sapientum*) processing waste, particularly banana peels, as sustainable adsorbents for water purification. Emphasis is placed on the structural properties, chemical composition, and global availability of banana biomass. Banana-derived materials are rich in amino acids, vitamins, polyphenols, and functional groups such as hydroxyl, carboxyl, amine, and carbonyl, which facilitate the adsorption of pollutants. Numerous studies demonstrate the efficacy of both raw and chemically modified banana peels in removing heavy metals—including Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}, Cr (VI), and Ni^{2+}, from aqueous solutions. Chemical modifications, including acid and alkali treatments, metal oxide incorporation, and hydrothermal carbonization, have significantly enhanced adsorption capacity by increasing surface area and functional group availability. Adsorption typically follows pseudo-second-order kinetics and aligns with Langmuir or *Freundlich* isotherms, indicating chemi-sorption and mono-layer adsorption mechanisms. Advanced composites, such as hydrogels and activated carbon infused with nano-

particles or chitosan, have achieved removal efficiencies exceeding 70 mg/g and demonstrated high re-usability over multiple cycles. These findings underscore the potential of banana peel-based materials as cost-effective, eco-friendly solutions for wastewater treatment. However, further research is recommended to evaluate performance in real-world environmental conditions and to scale up applications for industrial use.

Keywords: Banana (*Musa sapientum*); Agricultural waste; Natural adsorbents; Heavy metals removal; Adsorption isotherm models; Environmental remediation; Sustainable water purification.

Introduction

Water pollution posed significant environmental and public health challenges globally, particularly in regions with limited access to advanced treatment technologies. Adsorption methods were widely recognized as efficient, sustainable, and cost-effective strategies for the removal of various contaminants from aquatic environments (Ali *et al*., 2012). Concurrently, agricultural waste emerged as a valuable resource for developing low-cost sorbents, contributing to both environmental remediation and the valorization of biomass residues (Inyang *et al*., 2016).

Globally, researchers undertook extensive efforts to repurpose industrial and agricultural waste for water purification, aligning with broader goals of environmental conservation. Among agricultural byproducts, those rich in cellulose attracted growing attention due to their promising adsorption capabilities. Studies investigated their potential to remove a wide array of pollutants, including heavy metals, petroleum derivatives, synthetic dyes, pesticides, and other organic compounds.

The breadth of research in this field led to an increasing number of review articles focused on specific crop-derived wastes. This review provided a detailed assessment of banana peel waste as a viable adsorbent. Recent studies underscored the effectiveness of banana by-products in adsorbing various pollutants from water. However, despite these promising findings, available data remained fragmented and lacked comprehensive analysis.

Therefore, this review aimed to consolidate and critically evaluate current knowledge on the application of banana processing waste as absorbents for water decontamination, highlighting key findings and identifying gaps to guide future research.

2. Adsorption Methods for Contaminant Removal

2.1 Activated Carbon in Adsorption

Activated carbon was widely employed as an adsorbent across numerous applications, primarily due to its high surface area and well-developed porous structure. It effectively removed a broad spectrum of contaminants, including heavy metals, organic pollutants, and pesticides, as reported by Babel and Kurniawan (2003).

2.2 Biochar-Based Adsorption

Bio-char, a carbon-rich material produced via the pyrolysis of biomass, attracted considerable research interest owing to its impressive adsorption properties. Its porous morphology and surface chemistry facilitated the efficient removal of heavy metals, synthetic dyes, and organic compounds from aqueous solutions (Lehmann and Joseph, 2015).

3. Agricultural Waste-Derived Adsorbents

The use of agricultural waste for adsorbent production aligned well with circular economy principles. Studies demonstrated that natural materials such as rice husks, corn cobs, and fruit peels could be effectively converted into bio-based adsorbents. These materials showed strong performance in removing contaminants like heavy metals and dyes from water sources (Demirbas, 2008). Furthermore, such bio-adsorbents offered a sustainable and eco-friendly alternative to conventional materials, contributing to waste reduction and resource recovery efforts (Kurniawan *et al.*, 2006).

3.1 Agricultural Waste as Reagents for Contaminant Removal

Agricultural waste, often considered a low-value byproduct, offered substantial potential for developing reagents aimed at enhancing pollutant removal from aquatic environments. These materials served as economical and sustainable alternatives to conventional chemical reagents in water treatment processes.

3.2 Bio-char Production from Agricultural Residues

The pyrolysis of agricultural residues, such as rice straw and corn stalks, generated bio-char as a carbon-rich byproduct. This bio-char exhibited strong adsorption capabilities and was widely

investigated as an efficient adsorbent for removing various waterborne contaminants (Ahmad *et al*., 2014).

3.3 Functionalization of Agricultural Waste

Agricultural waste materials were frequently subjected to chemical modifications to improve their adsorption efficiency. Techniques such as grafting, hydrothermal treatment, and chemical activation using acids or bases successfully introduced functional groups onto the biomass surface, thereby enhancing its affinity for specific pollutants. For instance, chemically modified rice husk showed significantly improved performance in the removal of heavy metals from aqueous solutions (Hossain *et al*., 2011).

3.4 Utilization in Phyto-remediation

Certain agricultural crops demonstrated the ability to uptake and accumulate pollutants through their root systems. This process, known as rhizofiltration, employed plant roots to remove heavy metals, nutrients, and other contaminants from polluted water bodies. Research identified plant species such as sunflowers (*Helianthus annuus*) and cattails (*Typha spp.*) as effective candidates for extracting heavy metals and various organic and inorganic pollutants from aquatic environments (Salt *et al.*, 1998).

3.5 Botanical Description of the Banana Plant

The banana plant, one of the most widely cultivated tropical fruits globally, belonged to the genus *Musa* within the family *Musaceae*. Although commonly referred to as a tree, it was technically a large herbaceous plant. The banana plant comprised large, *rhizomatous* corms, broad leaves extending several meters in length, and a *pseudostem* formed by tightly wrapped leaf sheaths (Simmonds, 1966). It produced a single flowering stalk that developed into a large inflorescence, ultimately yielding a bunch of bananas. Commercially cultivated varieties were primarily *Musa acuminata* or hybrids between *Musa acuminata* and *Musa balbisiana* (Stover and Simmonds, 1987).

5. Uses of Banana Peels

5.1 Environmental Applications

Banana peels possessed functional groups such as carboxyl, hydroxyl, and amino groups, which played a key role in binding metal ions like lead (Pb^{2+}), cadmium (Cd^{2+}), and copper (Cu^{2+}) (Annadurai *et al.*, 2002). Studies demonstrated that both untreated and chemically modified banana peels acted as low-cost, eco-friendly bio-sorbents for removing contaminants from water (Pathak *et al*., 2015). Their availability, non-toxic nature, and biodegradability made them attractive for environmental remediation applications.

5.2 Agricultural and Industrial Uses

Banana peel biomass was effectively utilized in composting and the production of organic fertilizers due to its high nutrient content (Ayoola and Adeniyan, 2006). Additionally, the carbohydrate-rich composition of the peels supported their use in bio-ethanol and biogas production through fermentation processes (Oliveira *et al.*, 2007). In the field of materials science, banana peel-derived fibers and powders were incorporated into biodegradable plastics and composites, enhancing mechanical strength and sustainability (Sani *et al*., 2015).

5.3 Food and Medicinal Applications

Recent research explored the incorporation of banana peel flour into food products such as bread and biscuits to enhance dietary fiber content and reduce food waste (Kinsella *et al*., 2011). Moreover, the strong antioxidant and antimicrobial properties of banana peels indicated their potential in the development of nutraceuticals and alternative medicinal formulations (Mohapatra *et al*., 2010).

5.4 Application as Adsorption Materials for Pollutant Removal

Banana peels were widely investigated for their adsorption capabilities in removing heavy metal ions and synthetic dyes from aqueous media. Their abundant functional groups and porous structure enabled effective adsorption of pollutants, making them suitable candidates for low-cost water treatment solutions. Chemical modifications, such as acid treatment or base activation, further enhanced their adsorption efficiency, supporting their use in both laboratory-scale and pilot-scale studies.

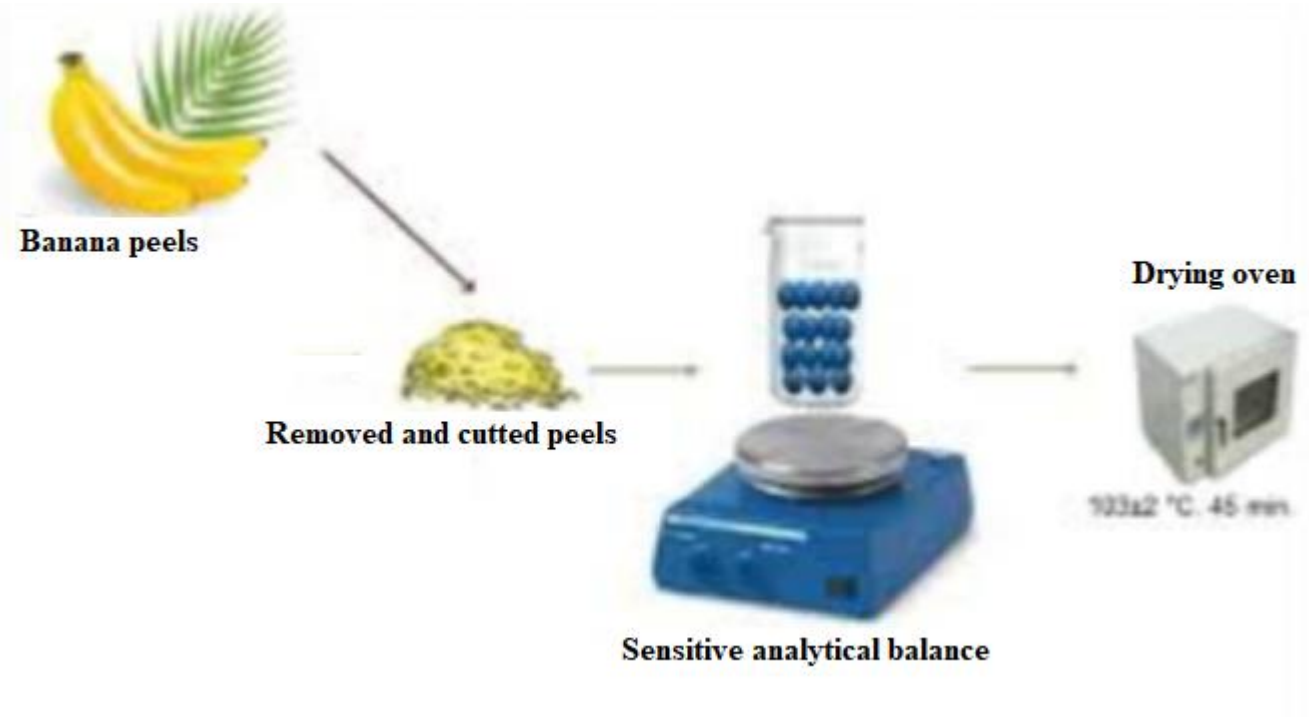


Fig.1: Processing steps for banana peels waste as adsorption material

6. Application of Banana Peels in the Removal of Metal Ions from Aqueous Media

Banana peels emerged as a promising bio-sorbent for the removal of heavy metal ions from contaminated water, owing to their abundance, low cost, and environmentally friendly characteristics. Numerous studies investigated their adsorption capabilities for various metal ions, including copper (Cu^{2+}), lead (Pb^{2+}), cadmium (Cd^{2+}), and iron (Fe^{2+}), drawing considerable attention within the research community.

In a 2017 study, Faisal evaluated the performance of banana peels in adsorbing Cu^{2+} ions from synthetic aqueous solutions. The results indicated that the optimal pH for maximum adsorption was 6, at which the adsorption capacity reached 52.63 mg/g. Kinetic modeling showed that the adsorption process conformed to a pseudo-second-order model, suggesting that chemi- sorption was the dominant mechanism.

In another study, conducted by Salim *et al*. (2016), sodium hydroxide was used to chemically modify banana peel powder, significantly enhancing its adsorption efficiency for Pb^{2+} and Cu^{2+} ions. The modified bio-sorbent exhibited superior performance compared to its unmodified counterpart, with maximum adsorption capacities of 89.29 mg/g for Pb^{2+} and 5.72 mg/g for

Cu^{2+}. The equilibrium data were well-fitted by both *Langmuir* and *Freundlich* isotherm models, indicating favorable adsorption behavior and multi-layer adsorption potential.

Praipipat *et al.* (2024) investigated Cd^{2+} removal using banana peel bio-char modified with zinc and magnesium oxides. The modified bio-char demonstrated a maximum adsorption capacity of 50.78 mg/g. The process was found to be both spontaneous and exothermic and followed a pseudo-first-order kinetic model, indicating physi-sorption as the primary mechanism.

In a 2021 study, Arifiyana and Devianti examined the use of Kepok banana peel for Fe^{2+} ion removal. Under optimal conditions, using 2.5 grams of adsorbent and an initial Fe^{2+} concentration of 60 mg/L—the material achieved an adsorption capacity of 0.6 mg/g. The adsorption was attributed to the presence of key functional groups, such as hydroxyl, carboxylic, and amine groups.

Overall, recent findings supported the potential of banana peels, both raw and chemically modified—as effective bio-adsorbents for the removal of heavy metals from aqueous solutions. Adsorption capacity was influenced by several factors, including pH, adsorbent dosage, contact time, and the presence of surface functional groups. Further research was recommended to optimize these parameters and assess the scalability and performance of banana peel-derived bio-adsorbents in real-world and industrial applications.

7. Polymerized and Activated Banana Peel-Based Bio-sorbents for Wastewater Treatment

Polymerized banana peels gained recognition as effective bio-sorbents for the removal of heavy metals from various wastewater sources, including domestic and industrial effluents. Their unique physico-chemical properties made them a viable and sustainable solution for addressing water contamination by toxic metals. A wide range of studies explored the potential of modified banana peel-based materials in wastewater purification.

In a study conducted by Sulianto *et al.* (2021), researchers developed novel pectin-based hydrogels by incorporating banana peel powder and carboxymethyl cellulose, followed by cross-linking with calcium chloride. These hydrogels exhibited a highly porous structure and substantial swelling capacity, both of which contributed to their enhanced performance in adsorbing heavy metals such as Cu^{2+}, Pb^{2+}, Cd^{2+}, and Ni^{2+}. The hydrogels achieved adsorption capacities exceeding 70 mg/g for all tested ions and demonstrated swelling rates greater than 80% at pH levels above 5. Furthermore, the materials retained their adsorption efficiency over five reuse cycles, underscoring their potential for sustainable wastewater treatment applications.

Jahin *et al*. (2024) examined the application of activated banana peels for the adsorption of heavy metals from wastewater. The study demonstrated that activated banana peels effectively removed Pb^{2+}, Cd^{2+}, and Cu^{2+} ions, with performance influenced by variables such as pH, contact time, and adsorbent dosage. The findings supported the use of activated banana peels as a low-cost, environmentally friendly bio-sorbent for water treatment applications.

In another recent case study, Pramanik *et al.* (2024) evaluated the efficacy of banana peel-derived activated carbon (BPAC) in treating industrial wastewater contaminated with heavy metals. The BPAC exhibited high removal efficiency for Pb^{2+}, with rates ranging from 75% to over 90%, and adsorption capacities reaching up to 6 mg/g. These results highlighted BPAC as a highly effective and sustainable bio-sorbent for the remediation of industrial effluents containing toxic metal pollutants.

8. Hydrogel and Composite Bio-sorbents Based on Banana Peels

Hydrogels synthesized from modified activated carbon (MAC) or polymerized banana peels (PBP) demonstrated high efficiency in the removal of heavy metals from wastewater. Due to their excellent adsorption capacity, re-usability, and low production cost, these materials presented a compelling alternative to conventional treatment methods. However, further research remained necessary to optimize their efficiency and support their scalability for large-scale wastewater treatment applications.

The literature extensively examined the use of polymerized banana peel powders and their composites with various bio-polymers as bio-sorbents and ion-exchange materials. Recent studies confirmed the effectiveness of these composite materials in removing toxic metal ions from aqueous solutions. Their popularity stemmed from their affordability, environmental sustainability, and ability to remove a range of pollutants, including Pb^{2+}, Cd^{2+}, Cr^{6+}, and Zn^{2+}.

In a study conducted by Boulaiche *et al.* (2018), the adsorption capacity of banana peel powder (BPP) for Cr^{6+} ions was evaluated. The maximum adsorption capacity was reported as 26.46 mg/g. Kinetic modeling indicated that the adsorption process followed both pseudo-first-order and pseudo-second-order models, while the Langmuir isotherm model provided the best fit for the equilibrium data. This suggested mono-layer adsorption on a homogeneous surface with limited active binding sites. Thermodynamic analysis revealed that the process was spontaneous and endothermic, with an activation energy of 1.56 kJ/moL, indicative of physical adsorption.

Sulaiman *et al*. (2021) investigated the use of calcium alginate beads loaded with banana peel powder for the removal of Zn^{2+}, Cr^{3+}, and Ni^{2+} from industrial wastewater. The beads also significantly reduced the concentrations of Fe, Pb, Cu, and Cr by 97%, 87%, 81%, and 80%, respectively. The adsorption kinetics conformed to a pseudo-second-order model, while the equilibrium data aligned with the Langmuir isotherm, indicating mono-layer adsorption on a surface with a finite number of uniform sites. The ion exchange mechanism was validated by a close correlation between the quantity of metal ions adsorbed and the corresponding amount of exchanged cations.

These findings underscored the potential of hydrogel and composite bio-sorbents derived from banana peels as sustainable, efficient solutions for metal ion removal in wastewater treatment systems.

9. Advanced Composite Materials Incorporating Banana Peels for Heavy Metal Removal

In 2022, Gupta and colleagues developed a novel composite adsorbent by layering aluminum oxide (Al_2O_3) and chitosan onto activated carbon derived from banana peels. This modification aimed to enhance the material's capacity to adsorb lead (Pb^{2+}) and cadmium (Cd^{2+}) ions. The resulting composite demonstrated improved structural stability and significantly higher adsorption efficiency compared to unmodified activated carbon. Characterization techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and Brunauer–Emmett–Teller (BET) surface analysis confirmed successful modification, with a notable increase in surface area contributing to enhanced adsorption performance.

In a separate study conducted by Mollah *et al.* (2021), researchers developed a composite material combining banana peel powder with potato peel. This bio-sorbent was tailored to remove Pb^{2+} ions from water and exhibited high adsorption efficiency and capacity. The adsorption process conformed to pseudo-second-order kinetics, while the Langmuir isotherm model provided the best fit to the equilibrium data, suggesting mono-layer adsorption on a uniform surface with a finite number of active sites.

Collectively, these studies demonstrated that composite materials incorporating banana peels, especially when functionalized or combined with nano-particles and bio-polymers, hold significant promise for the efficient and sustainable removal of heavy metals from contaminated water sources.

10. Acid-Modified and Composite Banana Peel Bio-sorbents

Recent studies underscored the substantial potential of polymerized banana peel powders, particularly when combined with various bio-materials to form composite materials. These composites emerged as promising ion exchange resins, demonstrating notable efficiency in capturing heavy metal ions from aqueous media. Their performance addressed critical environmental concerns associated with water contamination. The advantages of these bio-sorbents included low cost, environmental sustainability, and effective removal of toxic metals such as Pb^{2+}, Cd^{2+}, and Cr^{6+}. However, further research remained essential to optimize their properties and support their integration into large-scale wastewater treatment systems.

Current investigations also explored the effectiveness of acid-treated banana peel extracts as highly efficient bio-sorbents for metal ion removal. Chemical modifications significantly improved the surface properties of the biomass, increasing the availability of functional groups and enhancing its adsorption capacity.

Zhang *et al*. (2025) evaluated the performance of sulfuric acid-modified banana peel (ABP) in removing hexavalent chromium (Cr^{6+}) from aqueous solutions. The modification increased the surface area of the biomass, which resulted in a notable enhancement in adsorption capacity. Kinetic modeling revealed that the adsorption followed pseudo-second-order kinetics, while equilibrium data were best described by the *Langmuir* isotherm model. These findings indicated mono-layer adsorption on a homogeneous surface with a finite number of binding sites. Thermodynamic analyses further confirmed the spontaneous and endothermic nature of the process, with an activation energy of 2.5 kJ/moL, suggesting that physi-sorption was the dominant mechanism.

In another study, Milawati *et al.* (2024) focused on improving the adsorption capacity of banana peels for Pb^{2+} and Cd^{2+} ions typically found in landfill leachate. The researchers treated the peels with phosphoric acid, which facilitated the incorporation of functional groups such as carbonyl and carboxyl groups—key sites for metal ion binding. The treated peels demonstrated significantly higher adsorption efficiency compared to the untreated biomass, confirming the effectiveness of acid modification in enhancing the bio-sorptive properties of banana peel-based materials.

These findings emphasized the potential of chemically modified banana peels as sustainable and efficient bio-sorbents for water purification applications. Continued optimization of

treatment methods and material characterization is critical to advancing their practical use in environmental remediation.

11. Hydrothermal Carbonization and Acid Activation of Banana Peels for Heavy Metal Adsorption

In a 2021 study, Liu *et al.* investigated the hydrothermal carbonization of banana peels pre-treated with phosphoric acid, aiming to develop a bio-char adsorbent capable of efficiently removing Pb^{2+} ions from aqueous solutions. Phosphoric acid treatment enhanced the formation of oxygen-containing functional groups on the surface of the resulting bio-char, thereby increasing its adsorption capacity. Kinetic analysis revealed that the adsorption process followed a pseudo-second-order model, while equilibrium data conformed to the *Langmuir* isotherm, suggesting mono-layer adsorption on a homogeneous surface with a limited number of active sites.

Similarly, Tian *et al.* (2020) explored the modification of hydrothermal carbon derived from banana peels using potassium hydroxide (KOH) to improve its Pb^{2+} adsorption capabilities. The KOH treatment significantly enhanced the surface characteristics of the carbon by introducing various oxygen-containing functional groups, thereby increasing the number of active binding sites. The modified material exhibited an adsorption capacity of 2.92 mg/g and achieved a removal efficiency of 86.8% under optimized conditions, demonstrating its potential as an effective bio-sorbent.

These studies collectively demonstrated that acid modification significantly improved the metal ion adsorption capacity of banana peel-derived materials. The introduction of functional groups and the increase in surface area played a critical role in enhancing the number and accessibility of active sites. Such modifications presented a cost-effective and environmentally sustainable approach for the removal of heavy metals from contaminated water sources.

CONCLUSION

Banana peel waste, often overlooked as a mere byproduct, presented significant potential across various domains including medicine, agriculture, industry, and environmental science due to its rich chemical composition. Despite being frequently discarded, banana peels were identified as valuable sources of bio-active compounds, essential minerals, and dietary fibers. These attributes made them highly suitable for sustainable applications such as bio-sorption,

composting, bio-fuel production, the development of biodegradable materials, and functional food formulations.

This review highlighted the promising role of *Musa sapientum* (banana) peel and its derivatives as bio-sorbents for the removal of heavy metal ions and dyes from aqueous media. The paper synthesized existing findings on the structural properties, chemical composition, and treatment methods used to enhance the adsorption performance of banana biomass. Both native and chemically modified banana peels demonstrated effective removal capacities for several metal ions, including cadmium (Cd^{2+}), chromium (Cr^{6+}), copper (Cu^{2+}), nickel (Ni^{2+}), lead (Pb^{2+}), and zinc (Zn^{2+}).

Experimental studies showed that adsorption mechanisms generally followed pseudo-second-order kinetics and were best described by the Langmuir and Freundlich isotherm models. The effectiveness of banana peels as bio-sorbents was strongly influenced by factors such as pH, contact time, dosage, and the presence of key functional groups, including hydroxyl, carboxyl, amine, and carbonyl groups. Surface modification techniques such as acid activation, hydrothermal carbonization, polymerization, and nano-particle incorporation significantly enhanced both adsorption capacity and re-usability.

Banana peel-derived materials thus offered a low-cost, sustainable, and eco-friendly alternative to conventional adsorbents in wastewater treatment. However, despite these promising results, additional research remained necessary to advance the practical implementation of such materials in real-world treatment systems. Future studies should aim to: Optimize operational parameters under dynamic real-time conditions, conduct pilot- and full-scale trials to assess performance consistency, evaluate the regeneration and long-term stability of modified bio-sorbents, explore synergistic effects in composite or hybrid materials, carry out techno-economic and life-cycle assessments to determine scalability and environmental impact.

By addressing these areas, the application of banana peel-based bio-sorbents could be effectively integrated into modern water purification technologies, promoting both environmental protection and resource circularity.

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