RGA Global Journal of Multidisciplinary Research
ISSN : XXXX-XXXX | Vol 1, Issue 1, Jan – Feb, 2026
Published by RGA Research Publications

Synthesis, Modification and Application of Adsorbents Derived from Agro-Wastes: A Fundamental Review

Abidemi Anthony Sangoremi

Department of Chemistry, Federal University Otuoke, 400 University Boulevard Otuoke, PMB 126, Yenagoa, Bayelsa State, Nigeria

Received: 08 Jan 2026 | Accepted: 28 Jan 2026 | Published: 07 Feb 2026

Abstract

This review aims to explore the potential of agro-wastes as sustainable, low-cost precursors for adsorbent materials with a focus on advancing environmental sustainability and contributing to the global environmental circular economy. The study synthesizes information from recent literature on agro-waste materials such as rice husks, coconut shells, groundnut shells, banana peels, walnut shells, eggshells, snail shells, and corn cobs. It examines their chemical composition, synthesis techniques, and modification methods, including both physical and chemical alterations, in order to evaluate their adsorptive properties. Findings indicate that agro-waste derived adsorbents are abundant, renewable, and rich in lignocellulosic components that enhance adsorption performance. Their effectiveness in removing contaminants from wastewater and cleaning waste oils has been well-documented. Comparative analyses also reveal that some agro-wastes exhibit superior adsorptive capacities depending on their intrinsic material makeup. Despite significant advances, challenges remain regarding the scalability, standardization, and optimization of production methods for consistent industrial applications. Agro-waste derived adsorbents demonstrate high potential as eco-friendly and cost-effective alternatives to conventional adsorbents in environmental remediation. While progress has been made in their development and application, further research is required to overcome production limitations and to maximize their efficiency across diverse pollution removal scenarios. Their successful integration would strengthen sustainable practices and promote a circular economy.

Keywords: Coconut shells, Adsorbents, hemicellulose, lignin, renewability

1. Introduction

Wastes generated from agricultural sector are many, they constitute nuisance to the immediate environment where they are found, agricultural wastes are usually in large quantity, some of these wastes are known for their offensive odour, their decayed matter have ability to alter soil pH (Bello *et al*., 2017, Sangoremi, 2025). Recently, different research works have been carried out, in order to prepare adsorbents from these agricultural wastes used as an alternative to commercially available activated carbons, which are expensive (Onawumi *et al*., 2021). Presently, agricultural wastes materials have been proposed as economic and eco- friendly (Kumar and Kumar, 2014; Oladoja *et* *al*., 2014; Abdullahi *et al*., 2022). These protect the environment by getting rid of the danger such wastes pose to the environment, most especially where disposal of agricultural wastes has become a major problem (Bello *et al*., 2017). Environmental pollution, especially water contamination by heavy metals, dyes, and organic pollutants, has raised significant concerns. Traditional remediation methods often involve high operational costs and environmental side effects. Adsorption stands out as an efficient and eco-friendly alternative.

Agro-waste materials offer a sustainable solution due to their availability, low cost, and chemical characteristics suitable for adsorption (Sangoremi *et al*., 2024).

2. Sources and Applications of Agro-Wastes

Sources of agro-wastes are lignocellulosic wastes like rice husk, sugarcane bagasse, corn cobs, and wheat straw etcetera. While fruit wastes comprise banana peels, orange peels, coconut and shells, the list continues. Nut shells are groundnut shells, walnut shell, while animal shells include snail shell, eggshell, periwinkle shells (Ajala and Ali, 2020; Onawumi *et al*., 2021; Sangoremi *et al*., 2024). Fruits and vegetable residue are pineapple peels, orange peels, potato peels, onion skin peels. These wastes are rich in functional groups (-OH, -COOH, C=O, C≡N, $-NH_2$), and can be activated for enhanced adsorption performance (Onawumi *et al*., 2021; Sangoremi *et al*., 2024).

Agro-wastes had been used successfully in modern waste treatment plants for water filtration and detoxification treatment of impure waters (Ajala and Ali, 2020; Abraham *et al*., 2018; Jacob *et al*., 2017; Prusty and Patrol, 2015; Olagunju *et al*., 2015; Oladejo *et al*., 2014; Ijaola *et al*., 2013; Sivakumar *et al*., 2012), effluent and waste treatment (Ajayi-Banji *et al*., 2015; Marichelvan and Azhagurajam, 2018), adsorption of pesticide (Gokhale, 2020; Abdullahi *et al.,* 2022), waste oil adsorption (Nandini and Sivasakthivel, 2014) dye adsorption (Wu *et al*., 2020; Mansour *et al*., 2020; Ani *et al*., 2020), heavy metal sorption from aqueous media (Ijaola *et al*., 2013; Mopoung *et al*., 2015; Elelu *et al*.,2019), purification of used vegetable oil (Onawumi *et al*., 2017), oil palm fruit fibre by KOH activation and CO_2 gasification for removal of Malachite Green (Bello, 2013), sugarcane bagasse in recovery of used sunflower oil (Ali and El Anany, 2014) and prevention against novel Corona virus (SARS-CoV-2) (Reza *et al*., 2020). Commercial activated charcoals are expensive due to the use of non-renewable and relatively high cost starting materials such as coal which are not suitable with respect to environmental pollution control measure (Gupta *et al*., 2010, 2011, 2012; Olagunju *et al*., 2015; Abdullahi *et al.,* 2022).

There are different types of adsorbents derived from various forms of biomass which are economically produced by the activation and pyrolysis of renewable, readily available and, cheaper carbonaceous precursors which are mainly industrial and agricultural by-products such as groundnut and egg shells (Onawumi *et al*., 2017), bagasse (Ali and Anany, 2014; Ezeonuegbu *et al*., 2021), rice husk (Ajala and Ali, 2020), coconut shell (Saputro *et al*., 2020)), sawdust (Alzaydien, 2016), empty palm fruit bunch (Hidayat and Sutrisno, 2017), Physic nut waste (Elelu *et al*., 2019), pruning mulberry shoot (Wang *et al*., 2020, 2022), bamboo stem (Ijaola *et al*., 2013), chickpea (Ozsin *et al*., 2019), acorn shell (Saka, 2012). The process produces a porous material with a large surface area (500-1500 m^2/g) (Wang *et al*., 2020) and a high affinity for organic compounds, chlorine, heavy metals, objectionable tastes and odour in effluent or colour substances from gas or liquid streams (Ajala and Ali, 2020). This is possible as a result of their highly developed pore structure and large internal specific surface area (Mansour *et al*., 2020; Hidayat and Sutrisno, 2017).

However, the performance properties of biomass activated carbon (AC) depend largely on raw material source (Sivakumar *et al*., 2012). Adsorption of pollutants using agro-waste has become acceptable as a result of its versatility, environmental compatibility, relative abundance and low-cost starting materials, usually, waste products, adsorption of a broad range of pollutants, fast adsorption kinetics, and ease of production (Amirza *et al*., 2017; Mansor *et al*., 2020; Reza *et al*., 2020; Abdullahi *et al*., 2022). Adsorption process has been proven to be one of the best pollutants' treatment technologies globally, activated carbon is undoubtedly considered as a universal solution for the removal of different types of pollution in the environment (Bello *et al*., 2017; Ajala and Ali, 2020).

Activated carbons prepared from these precursors have been reported to be capable of removing metal ion and organic pollutants from aqueous solution (Babayemi, 2017b; Abraham *et al*., 2018). Activated carbon materials are characterized by their large surface areas, high carbon content, better porosity which are well-developed, and special surface reactivity (Ademiluyi *et al*., 2020; Nwabanne *et al*., 2022; Abdullahi *et al*., 2022). For these reasons, activated carbons are commercially used as adsorbents for the removal of organic chemicals and metal from the environment. Carbonaceous materials (animal), plant or mineral origin with high carbon content can be converted into activated carbon.

3. Synthesis of Agro-waste-Based Adsorbents

Agricultural wastes, such as fruit peels, nut shells, husks, stalks, leaves, and animal by-products like eggshells and bones, are rich in lignocellulosic components (cellulose, hemicellulose, and lignin) and inorganic materials (calcium carbonate, silica, etc.), making them suitable for adsorbent synthesis (Mishra et al., 2023). The valorization of these wastes into activated carbon or other functionalized adsorbents enhances their surface area, porosity, and adsorption potential for a wide range of pollutants. Common agricultural wastes used include: Coconut shells, rice husks, banana peels, orange peels, palm kernel shells, corncobs, sugarcane bagasse, eggshells and bone meal.

The synthesis of adsorbents from agricultural waste generally follows several key steps: Pre-treatment, which includes washing the raw biomass with distilled water to remove dirt, dust, and soluble impurities. The material is then dried at 60 –110 °C for several hours to remove moisture (Bhatti et al., 2022; Sangoremi et al., 2024), size reduction and sieving, dried materials are crushed and sieved to obtain uniform particle sizes, typically between 100–500 µm, which enhances activation efficiency and increases surface area. Followed by activation which is a critical step that transforms the precursor material into an efficient adsorbent by increasing its surface area, porosity, and functional group density. There are two primary method which are physical activation and chemical activation. Physical activation entails carbonization of the biomass at high temperatures (400–900 °C) under inert atmosphere (typically N_2 or CO_2), followed by gasification or activation using steam or CO_2. This method produces activated carbon with well-developed pore structures (Ioannidou & Zabaniotou, 2007). On the other hands, chemical activation utilizes chemical agents such as phosphoric acid (H_3PO_4), potassium hydroxide (KOH), zinc chloride ($ZnCl_2$), or sodium hydroxide (NaOH) to impregnate the biomass before carbonization. This method is favored for its lower activation temperature and higher surface area output (Mohd Din et al., 2023). The biomass is impregnated with the activating agent at a specific ratio (typically 1:1 to 1:3), left to soak for several hours, and then heated to activation temperature. Chemical activation is back-up by calcination which ensures that the impregnated biomass is carbonized in a muffle or tubular furnace at a temperature range of 400 – 800 °C. The carbonization process drives off volatile matter and creates the porous structure necessary for adsorption (Hameed et al., 2008). This is followed by washing and drying which also regarded as a post-carbonization process whereby the adsorbent is washed with distilled water or dilute acids (e.g., HCl) to remove residual activating agents and soluble impurities, followed by drying in an oven. Finally, further enhance adsorption efficiency, functionalization with oxidizing agents (e.g., nitric acid), amines, thiols, or nanomaterials (e.g., Fe_3O_4 nanoparticles) can be performed to introduce specific functional groups (e.g., –OH, –COOH, $–NH_2$) (Saleem et al., 2022).

4. Modification Techniques

These materials, often derived from abundant and renewable biomass resources such as fruit peels, shells, husks, straws, and stalks, possess significant adsorption capacities due to their inherent porosity and surface functional groups. However, the raw (unmodified) forms of these biomaterials often suffer from limitations such as low surface area, inadequate porosity, limited adsorption sites, and poor selectivity. To overcome these challenges and enhance their adsorption performance, modification techniques are applied. These modifications tailor the physicochemical characteristics of the adsorbents to improve parameters such as surface area, pore size distribution, mechanical strength, thermal stability, and affinity for specific pollutants. Natural agricultural wastes, although cheap and environmentally benign, often lack the necessary properties to function efficiently as high-performance adsorbents in wastewater treatment. Their modification becomes essential to increase surface area and pore volume, improve the accessibility and number of functional groups, enhance the hydrophobic/hydrophilic balance, introduce specific functional moieties for targeted adsorption, improve thermal and chemical stability under different conditions (Foo & Hameed, 2012; Yakout et al., 2022). Modifications, therefore, transform agricultural waste into value-added products with competitive adsorption efficiency comparable to commercial activated carbon and other synthetic materials. Modification of agricultural waste-based adsorbents can be broadly categorized into physical, chemical, and biological methods. Sometimes, combinations of these techniques are used to maximize performance. Physical modification typically involves mechanical, thermal, or irradiation treatments. For instance, carbonization transforms raw biomass into carbon-rich adsorbents by heating under inert atmospheres, while activation (physical or chemical) increases porosity and surface area. Physical activation employs gases like CO_2 or steam at high temperatures (600–900°C), whereas chemical activation uses agents like KOH, H_3PO_4, or $ZnCl_2$. For example, Musa et al. (2023) reported that thermal activation of coconut shell waste at 800°C produced adsorbents with high microporosity and surface area, suitable for dye and metal ion adsorption. Another method is microwave-assisted activation which is a fast and energy-efficient approach to generate porous structures. Ultrasonic waves, on the other hand, help in disintegrating the surface structure, thereby increasing surface roughness and functional group availability (Zhang et al., 2022). Also, the chemical modification is perhaps the most widely used approach. It introduces or alters functional groups such as: –OH, –COOH, $–NH_2$, and $–SO_3H$, enhancing the interaction with adsorbates. Acid treatment (e.g., with H_2SO_4, HCl, or HNO_3) removes impurities and introduces acidic functional groups, which increase metal ion binding. Alkali treatment (e.g., with NaOH or KOH) opens up the lignocellulosic matrix and introduces hydroxyl groups. For instance, NaOH-modified rice husk showed improved adsorption of phenolic compounds and heavy metals due to increased porosity and hydroxyl functional groups (Ali et al., 2021). In addition, oxidizing agents are also employed such as H_2O_2, ozone, or $KMnO_4$ are used to oxidize the surface and create active sites. This improves interactions with anionic pollutants through electrostatic or hydrogen bonding interactions. Grafting involves chemically attaching polymeric chains or molecules (e.g., amines, thiols) to the adsorbent surface. For instance, grafting polyethyleneimine (PEI) onto biochar significantly enhanced its selectivity and uptake capacity for Cr (VI) ions (Li et al., 2022). Further, impregnation with metal Ions or nanoparticles are also employed by incorporating iron, aluminum, or manganese oxides improves adsorbent affinity for phosphates and arsenates. Similarly, impregnation with magnetic nanoparticles facilitates magnetic separation post-adsorption (Shaheen et al., 2020).

Biological modification leverages microbes or enzymes to pre-treat biomass, breaking down complex polymers like lignin and hemicellulose. While less common than chemical methods, this green approach is gaining traction. For instance, white-rot fungi have been used to degrade lignin in wheat straw, enhancing its adsorption capacity for organic dyes (Yang et al., 2023).

5. Characterization of Adsorbents

To optimize their performance as adsorbents, comprehensive characterization is essential to understand their physicochemical properties and surface functionalities. Characterization serves as the foundation for evaluating the suitability of agricultural wastes for adsorption processes, guiding the synthesis, modification, and application of these materials in environmental and industrial contexts (Bhatnagar et al., 2015; Kalavathy et al., 2023). Characterization provides critical information on the surface area and porosity, functional groups, elemental composition, thermal stability, crystalline structure, morphology and surface texture. These properties influence the adsorption mechanisms, capacity, kinetics, and thermodynamics of the process (Demiral & Güngör, 2016, Onawumi et al., 2021; Sangoremi et al., 2024).

The characterization techniques include proximate and ultimate analysis which are used in determining moisture content, ash content, volatile matter, and fixed carbon, which are essential for evaluating the combustibility and carbonaceous content of the biomass. Furthermore, ultimate analysis evaluates elemental composition (C, H, N, S, O) using CHNS analyzers. These results help in determining the suitability of the material as a carbon precursor for activated carbon production (Jain et al., 2021). Another technique is Fourier Transform Infrared Spectroscopy (FTIR) which identifies the functional groups present on the adsorbent surface, which interact with pollutants during adsorption. Functional groups like hydroxyl (-OH), carbonyl (-C=O), carboxyl (-COOH), and amine (-NH2) play vital roles in binding heavy metals or dyes (Gul et al., 2022). For example, FTIR analysis of coconut husk revealed strong peaks corresponding to –OH and –COOH, which facilitated cadmium adsorption (Salleh et al., 2020). Also, the Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS). SEM provides insights into the surface morphology of the adsorbents, such as porosity, roughness, and the presence of cracks, which influence surface accessibility for adsorbates. While EDS complements SEM by providing elemental analysis and mapping, confirming the presence of elements like C, O, K, Ca, and adsorbed heavy metals after treatment (Amin et al., 2021). Brunauer–Emmett–Teller (BET) measures surface area, pore size distribution, and pore volume of the adsorbent. These properties are critical for assessing adsorption capacity. Agricultural wastes activated at high temperatures or with chemicals such as phosphoric acid or KOH generally show improved BET surface areas, sometimes exceeding 1000 m^2/g (Muthulakshmi et al., 2023). In addition to Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC). The thermal analyses reveal the thermal stability and decomposition patterns of agricultural biomass while TGA identifies the temperature ranges for the loss of moisture, hemicellulose, cellulose, and lignin, which aids in selecting optimal carbonization temperatures. DSC provides heat flow data, indicating endothermic and exothermic transitions during pyrolysis (Ramanayaka et al., 2022). In addition to X-Ray Diffraction (XRD) which determines the crystalline or amorphous nature of the adsorbent. Agricultural wastes typically exhibit broad peaks indicative of amorphous cellulose and lignin structures. Post-carbonization, XRD may show sharper peaks indicating the development of graphitic microstructures (Kumar et al., 2020). Finally, the pH at Point of Zero Charge (pHpzc) is the pH at which the surface charge of the adsorbent is neutral. This parameter influences the interaction between the adsorbent and adsorbate, especially in aqueous media. Agricultural waste-based adsorbents often have pHpzc values in the range of 4 to 8, depending on treatment (Abukhadra et al., 2023).

The factors that influence adsorbent characterization include: Pre-treatment methods which can be physical (grinding, washing), thermal (carbonization), and chemical (acid/base activation) treatments significantly modify surface properties and affect characterization results (Chen et al., 2023). Also, the type of agricultural waste which may those that are high-lignin materials (e.g., coconut shell) tend to form harder carbon structures with higher surface area, while cellulose-rich wastes (e.g., corn husk) may yield different pore structures (Ioannidou & Zabaniotou, 2021). Activation Conditions such as temperature, duration, and activating agents (H_3PO_4, KOH, $ZnCl_2$) play pivotal roles in tuning the porous network and functional groups (Yakout & El-Deen, 2022).

6. Applications in Environmental Remediation

Environmental contamination, particularly from industrialization, urbanization, and agricultural activities, has become a global challenge, posing serious threats to ecosystems and human health. Key environmental pollutants include heavy metals, dyes, pesticides, pharmaceutical residues, oils, and emerging organic contaminants (EOCs). Traditional remediation methods such as chemical precipitation, ion exchange, electrochemical treatment, and reverse osmosis are often costly, energy-intensive, and may generate toxic sludge (Giwa et al., 2021). As a result, there is growing interest in low-cost, sustainable, and efficient alternatives, particularly adsorption-based technologies utilizing agricultural waste materials as adsorbents. Agricultural wastes, abundantly available and biodegradable, present a renewable source for developing eco-friendly adsorbents. These materials often contain cellulose, hemicellulose, lignin, proteins, and functional groups (e.g., hydroxyl, carboxyl, amino), which enhance their adsorption potential for various environmental pollutants (Bello et al., 2019; Ayanda et al., 2022). This write-up extensively discusses the application of agricultural waste-based adsorbents in environmental remediation, supported by recent scholarly contributions. Agricultural wastes such as rice husks, coconut shells, banana peels, orange peels, corn cobs, sawdust, sugarcane bagasse, palm kernel shells, and groundnut shells have been extensively investigated for their adsorption capabilities. These wastes, after proper modification or activation (thermal or chemical), exhibit high surface areas, porosity, and active functional groups suitable for environmental remediation applications (Okoya et al., 2023). For instance, activated carbon derived from coconut shells and rice husks has been reported to be highly efficient in removing dyes and heavy metals from wastewater (Olaniyan et al., 2023). Also, Sangoremi et al. (2024) used modified groundnut shell adsorbent to remove Bromocresol green dye from wastewater, and the studies went further to analysis the kinetic parameters during the adsorption process. In addition, Sangoremi et al., (2025), applied modified groundnut shell adsorbent to regenerate spent vegetable oil by removing the peroxide, free fatty and acid. The experimental data for both the kinetics and isotherms were further analysed and fitted into models.

Similarly, banana peels have been modified to adsorb cadmium and lead ions due to their high pectin and lignin content, which offer multiple binding sites (Nasirudeen et al., 2022). Heavy metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), mercury (Hg^{2+}), chromium (Cr^{6+}), zinc (Zn^{2+}), and copper (Cu^{2+}) are non-biodegradable and persist in the environment, leading to bioaccumulation and toxicity. Agricultural waste-based adsorbents have demonstrated considerable effectiveness in removing these metals from contaminated water. Orange peel activated carbon showed excellent adsorption for Pb^{2+} due to the presence of hydroxyl and carboxyl functional groups (Anwar et al., 2021). Also, modified rice husk adsorbent exhibited high efficiency in removing Cr^{6+} from tannery effluent (Kumar et al., 2022). In addition, groundnut shells chemically treated with phosphoric acid have shown enhanced removal of Cu^{2+} from aqueous solutions (Ibrahim et al., 2023). The removal mechanism typically involves ion exchange, electrostatic attraction, complexation, and surface precipitation, depending on the pollutant and the surface chemistry of the adsorbent. Furthermore, the synthetic dyes from the textile, leather, and paper industries are one of the most polluting and toxic organic contaminants. Dyes such as methylene blue, Congo red, malachite green, and Acid Red 87 are resistant to photodegradation and microbial decomposition.

Agricultural waste-based adsorbents have demonstrated significant potential in dye removal: Activated eggshells and coconut coir pith adsorbents effectively removed Acid Red 87 from aqueous systems (Sanni et al., 2024). Also, sawdust-based activated carbon showed high adsorption capacity for methylene blue through π-π interactions and pore filling (Giwa et al., 2021). Corn cob-derived adsorbents removed Congo red efficiently under acidic conditions due to electrostatic interactions (Omole et al., 2023). Spent engine oil, lubricants, and petroleum hydrocarbons from industrial spills and vehicle operations cause significant soil and water pollution. Agricultural wastes can be used to adsorb these non-polar contaminants due to their hydrophobic properties after thermal treatment (Sangoremi et al., 2023; Sangoremi et al., 2025). Palm kernel shell biochar demonstrated high sorption capacity for spent engine oil, attributed to its porous structure and large surface area (Adeleke et al., 2022). Likewise, sawdust and rice husk ash were used in the remediation of oil-contaminated soils, significantly improving soil physicochemical properties post-treatment (Nwachukwu et al., 2021). Similarly, modified coconut fiber has been utilized in oil-spill cleanup operations, showing high reusability and adsorption efficiency (Mohammed et al., 2023). Emerging pollutants such as pharmaceutical residues, endocrine-disrupting compounds (EDCs), pesticides, and microplastics are of increasing concern. Conventional water treatment plants are often ineffective against them. Biochar from sugarcane bagasse showed adsorption for paracetamol and ibuprofen, with hydrogen bonding and π-π electron donor–acceptor interactions being key mechanisms (Rahman et al., 2023). Further, orange peel activated carbon has been reported for atrazine and glyphosate pesticide removal due to its microporous nature and functional groups (Onwukeme et al., 2022). In the same manner, contaminated soils and sediments containing heavy metals, hydrocarbons, and persistent organic pollutants (POPs) pose long-term environmental risks. The application of agricultural waste-based bioadsorbents in in-situ soil remediation is gaining momentum. Composted cassava peels and cow dung have been successfully used to reduce total petroleum hydrocarbons (TPH) in polluted soils (Ogunyemi et al., 2023), and biochar from maize stalks improved the immobilization of Pb and Zn in contaminated mining soil, reducing leachability and bioavailability (Afolabi et al., 2024).

7. Advantages and Challenges

Agro-wastes abundant availability, low cost, and environmental compatibility make them attractive candidates for the adsorption of pollutants in water and air Agricultural residues are produced in large quantities globally, especially in developing countries with agrarian economies. According to FAO (2023), the global annual generation of agricultural biomass exceeds 5 billion tonnes, much of which is underutilized. Utilizing this waste as adsorbents provides a low-cost raw material source that does not compete with food production or land use (Khan et al., 2023). For instance, rice husk, a by-product of rice milling, is produced in millions of tons annually and is often discarded or burned, causing environmental pollution. Converting such residues into adsorbents not only reduces waste but also adds economic value. Using agricultural wastes for adsorbent production aligns with the principles of the circular economy and sustainable development. It helps in waste valorization, minimizing environmental pollution caused by the open burning or indiscriminate disposal of biomass (Ifelebuegu et al., 2022). Moreover, the carbon footprint associated with the synthesis of agricultural adsorbents is considerably lower than that of conventional activated carbon derived from coal or petroleum sources (Zubair et al., 2024). Many agricultural wastes are rich in lignocellulosic components such as cellulose, hemicellulose, and lignin, which can be chemically modified to introduce various functional groups (e.g., –OH, –COOH, $–NH_2$). These functional groups play critical roles in adsorbing pollutants such as heavy metals, dyes, and oils (Ganiyu et al., 2023). For example, modified banana peels and coconut shells have demonstrated excellent adsorption capacities for heavy metals like lead and cadmium due to the presence of carboxylic and hydroxyl groups (Obiora et al., 2023). Unlike synthetic adsorbents, agricultural waste-based adsorbents are biodegradable and pose minimal environmental and health hazards during disposal. Their natural origin ensures reduced ecotoxicological impact, which is a crucial consideration for sustainable waste management strategies (Onwukeme et al., 2023). Agricultural waste adsorbents can be easily modified through physical (e.g., carbonization, activation), chemical (e.g., acid/base treatment), and biological treatments to enhance their adsorption efficiency (Nasrullah et al., 2023). These modifications expand their applications across various domains such as wastewater treatment, air purification, and oil spill remediation.

One of the major drawbacks is the heterogeneity of agricultural waste materials. Factors such as plant species, cultivation methods, harvesting time, and geographic origin can influence the chemical composition and structural characteristics of the biomass, resulting in inconsistent adsorption performance (Ali et al., 2024). However, despite the numerous advantages, several challenges must be addressed to optimize their use on a large scale which include low surface area and porosity especially in raw form. Many raw agricultural wastes have limited surface area and poorly developed pore structures compared to commercial activated carbons. As adsorption is a surface-driven process, these physical limitations reduce the efficiency of pollutant uptake unless the biomass is appropriately treated or activated (Ismail et al., 2024). Hence, extensive processing is often required to increase surface area and functional groups, which may offset some of the cost advantages. Also, while raw agricultural wastes are cheap, they often require chemical, thermal, or physical activation to enhance their adsorption properties. These processes may involve the use of chemicals like phosphoric acid, potassium hydroxide, or zinc chloride, which introduce concerns about secondary pollution and additional operational costs (Agboola et al., 2023). Moreover, process optimization for different wastes is required, and this complexity can hinder the development of universal treatment protocols. In addition, regeneration and reuse of agricultural adsorbents are often limited due to their thermal instability and tendency to degrade after repeated use. Some bioadsorbents show reduced efficiency after a few cycles, and their structural integrity may not withstand harsh regeneration methods (Adeyemi et al., 2024). This limits their practical applicability in long-term industrial-scale operations unless more durable modifications are applied. Furthermore, spent adsorbents saturated with hazardous pollutants may pose disposal challenges. If not properly treated, they can leach adsorbed contaminants back into the environment. Furthermore, the lack of standardized guidelines for the safe disposal or regeneration of such materials may undermine their eco-friendly nature (Chukwuma et al., 2024). Finally, despite growing academic interest, the industrial-scale commercialization of agricultural waste-based adsorbents remains limited. Regulatory barriers, lack of funding, insufficient infrastructure, and low public awareness hamper the adoption of these materials in conventional wastewater treatment facilities (Ifelebuegu et al., 2022).

8. Future perspectives

Presently, agricultural waste-based adsorbents have emerged as sustainable, cost-effective, and eco-friendly alternatives to conventional materials for removing pollutants from air, water, and soil. As global attention shifts toward cleaner technologies and waste valorization within the circular economy paradigm, the future of agricultural waste-derived adsorbents holds significant promise. These materials—originating from fruit peels, nutshells, husks, straws, stalks, seeds, and other lignocellulosic biomass—are being researched and developed not just for environmental remediation but also for advanced technological applications such as catalysis, energy storage, and sensor technologies (Inyang et al., 2021; Yin et al., 2023). The global push for circular economy principles positions agricultural waste-based adsorbents as central to sustainable material management. Instead of burning or landfilling, agricultural residues can be upcycled into high-value adsorbents, thereby closing the loop in agricultural and industrial systems (Georgiou et al., 2023). This transformation aligns with global zero-waste strategies and supports Sustainable Development Goals (SDGs), particularly SDG 12 (responsible consumption and production) and SDG 6 (clean water and sanitation). Future systems are expected to integrate decentralized biomass conversion units for local production of adsorbents, thus reducing the carbon footprint associated with transportation and processing. Moreover, large-scale biorefineries may combine the extraction of bio-based chemicals with the synthesis of adsorbents, maximizing value from waste streams (Alhogbi, 2021). The efficacy of raw agricultural waste adsorbents is limited by factors such as low surface area, pore volume, and surface reactivity. The future lies in the advanced physical, chemical, and biological modification techniques such as chemical activation using acids (HCl, H_3PO_4), bases (KOH, NaOH), or oxidizing agents (H_2O_2) to introduce surface functional groups and increase adsorption sites. Also, microwave-assisted pyrolysis and supercritical fluid treatment to improve porosity and reduce processing time (Wang et al., 2023). Furthermore, nano-structuring and composite formation with metal oxides, carbon nanotubes, or magnetic nanoparticles to create hybrid adsorbents with enhanced selectivity and recyclability (Hadi et al., 2024). Future research is expected to focus on precision-engineering of adsorbents at the nanoscale using green synthesis approaches, enabling tailored surface properties for specific pollutants, such as heavy metals, pharmaceuticals, or dyes.

Another promising direction is the development of smart adsorbents materials that respond to environmental stimuli (pH, temperature, magnetic field, light). Agricultural waste can be used as a base material for synthesizing stimuli-responsive polymers or magnetically-separable composites, which improve reusability and process control in environmental applications (Zhao et al., 2022). For instance, magnetically activated biochar from rice husk or coconut shell can be easily recovered post-treatment using external magnets, reducing the cost of regeneration and secondary pollution risks. Moreover, In the future, agricultural waste-derived adsorbents are likely to find applications beyond conventional pollutant removal. Emerging areas include: Activated carbons from agricultural waste have shown potential in supercapacitors and lithium-ion batteries due to their high surface area and electrochemical stability (Rajesh et al., 2023). Biochar and activated carbon materials from biomass are being explored as catalysts or catalyst supports in chemical reactions, including biodiesel production and advanced oxidation processes (AOPs) (Nasrullah et al., 2022). With further development, these materials could serve in CO_2 capture, methane adsorption, or hydrogen storage. The multifunctionality of these materials is expected to revolutionize their application scope, transitioning them from waste management tools to advanced functional materials in various industrial sectors. Despite widespread laboratory-scale research, the industrial adoption of agricultural waste adsorbents remains limited due to challenges in standardization, supply chain logistics, cost-effectiveness, and regulatory approval. However, future perspectives include: Techno-economic assessments and life cycle analyses (LCA) to validate the sustainability and economic viability of large-scale production (Kumar et al., 2023). Public-private partnerships (PPP) to promote start-ups and SMEs involved in the production of bio-adsorbents from agricultural residues. Incentive policies and governmental regulations to promote waste valorization technologies and green product certifications. Industrial-scale adsorbent production units near agricultural hubs (e.g., palm oil mills, rice processing zones) could help harness raw biomass efficiently, thus reducing waste management costs and creating new job opportunities. AI and ML are increasingly being integrated into materials science for predictive modeling, optimization, and design of experiments (DoE). These tools will play a significant role in the future of agricultural waste-based adsorbent development by predicting adsorption capacities based on surface chemistry and morphology, optimizing synthesis and activation conditions, accelerating screening processes for new agricultural waste candidates. AI-driven databases and machine learning algorithms can greatly enhance the efficiency and success rate of adsorbent research (Shen et al., 2023). Future utilization of agricultural waste-based adsorbents will also depend on enabling policies, community participation, and education. Governments and environmental agencies must promote green procurement standards that favor bio-based adsorbents, fund research and innovation grants for sustainable materials development, support capacity building in low- and middle-income countries where agricultural waste is abundant but underutilized, and public education campaigns can increase acceptance and awareness of these materials, especially in water-stressed regions where access to clean water is limited.

9. Conclusion

Agricultural waste-based adsorbents have emerged as promising, sustainable, and low-cost alternatives for environmental remediation. Their widespread availability, eco-friendliness, and rich surface chemistry make them suitable for removing diverse pollutants from water, air, and soil. Although some challenges remain, ongoing research and technological innovations are expected to expand their industrial application and enhance their efficiency. These materials offer a critical solution at the nexus of waste management and pollution control, contributing significantly to sustainable environmental practices and enhanced global circular economy.

Article Publication Details

This article is published in the **RGA Global Journal of Multidisciplinary Research**, ISSN XXXX-XXXX (Online). In Volume 1 (2026), Issue 1 (January - February)

The journal is published and managed by **RGA Research Publications**.

References

1. Abdullahi, A., Tsafe, A.I., Liman, M.G., and Ibrahim, N. (2022). Characterization and Modification of Activated Carbon Generated from Annogeissus leiocarpus. Caliphate Journal of Science and Technology (CaJoST) 2, 151-159.
2. Abraham, F.A., Thenmozhi, R., Sivakumar, M., Sivakumar, K., Sasikumar, G. and Thamaraimuthuayyanraj, S. (2018). Waste water treatment unit using activated charcoal. International Resource. Journal of Engineering and Technology, 5 (3):312-315.
3. Abukhadra, M. R., Abd El-salam, H. M., & Bakry, A. M. (2023). Characterization and environmental application of sugarcane bagasse-based adsorbent for dye removal. Environmental Research, 226, 115664.
4. Adeleke, B. O., Oladipo, A. A., & Folarin, M. O. (2022). Adsorptive removal of spent engine oil using palm kernel shell biochar: Characterization and kinetic studies. Environmental Technology & Innovation, 28, 102935.
5. Ademiluyi, M.F., Adebayo, M.A., Akinola, A.O., Olasehinde, E.F., Adewole, K.A., and Lajide, L. (2020). Preparation and characterization of biochars from elephant grass and the

utilization for aqueous nitrate removal effect of pyrolysis temperature. Journal of Environmental and Chemical Engineering, 8 (2020):104507.

6. Adeyemi, A. T., Ogundiran, M. B., & Alade, A. O. (2024). Regeneration potential of agro-waste-based adsorbents for wastewater treatment: A review. Environmental Nanotechnology, Monitoring & Management, 23, 100818.
7. Adeyi, A.A., Omotola, E.O., & Ighalo, J.O. (2021). Phosphate adsorption using agricultural waste-based adsorbents: A comprehensive review. Environmental Technology & Innovation, 21, 101298. https://doi.org/10.1016/j.eti.2020.101298
8. Afolabi, A. S., Okonkwo, C. A., & Adeyemi, T. O. (2024). Biochar from maize stalk for remediation of heavy-metal-contaminated soil. Environmental Earth Sciences, 83(1), 17.
9. Agboola, M. O., Alabi, A. B., & Ahmed, Y. (2023). Chemical activation of agricultural biomass for enhanced adsorption of pollutants: A systematic review. Cleaner Engineering and Technology, 12, 100548.
10. Ajala, L.O and Ali, E.E. (2020). Preparation and Characterization of Groundnut Shell-Based Activated Charcoal. Journal of Applied Sciences and Environmental. Management, 24 (12):2139-2146.
11. Ajayi-Banji, A., Sangodoyin, A. and Ijaola, O. (2015). Coconut husk Char Biosorptivity in Heavy Metal Diminution from Contaminated Surface Water. Journal of Engineering Studies and Research, 21 (4):7-13.
12. Alhogbi, B. G. (2021). Agricultural waste for wastewater treatment: A review on biosorbents, biochar, and biopolymers. Journal of Environmental Chemical Engineering, 9(4), 105931. https://doi.org/10.1016/j.jece.2021.105931
13. Ali, I., Basheer, A.A., & Khan, T.A. (2021). Low-cost adsorbents for the removal of organic pollutants from wastewater. Journal of Environmental Chemical Engineering, 9(4), 105675. https://doi.org/10.1016/j.jece.2021.105675
14. Ali, M., Khan, M. N., & Shahid, M. (2024). Agricultural waste as a sustainable source for adsorbent production: An insight into chemical composition variability and its impact. Journal of Environmental Management, 339, 118341.
15. Ali, R.F., and El Anany, A.M. (2014). Recovery of Used Frying Vegetable Oil with sugar Cane Industry and Hot Water. Journal of Food Science and Technology 51 (11):13002-13012.
16. Alizaydien, A.S. (2016). Physical chemical and adsorptive characteristics of local oak sawdust based activated carbons. Asian Journal Science Research 9, 45-36.
17. Amin, M. T., Alazba, A. A., & Shafiq, M. (2021). Utilization of modified date pits for wastewater treatment: Characterization and isotherm studies. Journal of Environmental Management, 287, 112296.
18. Amirza, M.A.R., Adib, M.M.R. and Hamdan, R. (2017). Application of agricultural wastes activated carbon for dye removal: An overview, MATEC Web of Conference 103, 1-12.
19. Ani, J.U., Akpomie, K.G., Okoro, U.C., Aneke, L.E., Onukwuli, O.D., and 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 (69):1-11.

20. Ayanda, O. S., Oyetade, O. A., & Olaniran, A. O. (2022). Agricultural waste-derived adsorbents for heavy metal removal from wastewater: A review. Journal of Environmental Management, 301, 113865.
21. Babayemi, A. K. (2017b). Performance Evaluation of Palm Kernel Shell Adsorbents for the Removal of Phosphorus from Wastewater. Advances in Chemical Engineering and Science, 7 (2):215–227.
22. Bello, O. S. (2019). Agricultural waste-based adsorbents for the removal of water pollutants: A review. Bioresource Technology Reports, 7, 100261.
23. Bello, O.S., Awojuyigbe, E.S., Babatunde, M.A. and Folaranmi, F.E. (2017). Sustainable conversion of agro-wastes into useful adsorbent. Applied Water Science 7, 3561-3571.
24. Bhatnagar, A., Hogland, W., Marques, M., & Sillanpää, M. (2015). An overview of the modification methods of agricultural waste-based adsorbents for water treatment. Environmental Technology, 36(3), 279–290.
25. Bhatti, H. N., Iqbal, M., & Noreen, S. (2022). Agricultural Waste-Derived Adsorbents for Water Pollution Control: Current Status and Future Perspectives. Environmental Nanotechnology, Monitoring & Management, 18, 100753. https://doi.org/10.1016/j.enmm.2022.100753
26. Chen, W., Xu, Z., & Liu, Y. (2023). Advances in agricultural waste-derived biochar characterization and its application in water decontamination. Journal of Hazardous Materials, 451, 131132.
27. Chukwuma, E. C., Okeke, U. C., & Nwankwo, J. C. (2024). Post-adsorption management and disposal techniques of spent bio-adsorbents: Challenges and prospects. Waste Management & Research, 42(3), 215–226.
28. Dahri, M. K., Kooh, M. R. R., & Lim, L. B. L. (2019). Remediation of Environmental Pollutants Using Agricultural Waste-Based Adsorbents: A Review. Ecotoxicology and Environmental Safety, 168, 185–206. https://doi.org/10.1016/j.ecoenv.2018.10.043
29. Demiral, H., & Güngör, C. (2016). Adsorption of copper (II) from aqueous solutions on activated carbon prepared from grape bagasse. Journal of Cleaner Production, 124, 103-113.
30. Elelu, S., Adebayo, G.B., Abduls-Salam, N. and Iriowen, E.M. (2019). Preparation and characterization of adsorbents from physic nut plant (Jatropha curcas L). The Chemist, 91 (2):42-49.
31. Ezeonuegbu, B.A., Machido, D.A., Whong, C.M.Z., Japhet, W.S., Alexiou, A., Elazab, S.T., Qusty, N.,Yaro, C.A., and Batiha, G.E. (2021). Agricultural waste of sugarcane bagasse as efficient adsorbent for lead and nickel removal from untreated wastewater: Biosorption, equilibrium isotherms, kinetics and desorption studies. Biotechnology Reports 30, 1-14.

32. FAO (2023). World Agriculture Statistics: Biomass and Waste Resources. Food and Agriculture Organization of the United Nations. https://www.fao.org/statistics
33. Foo, K.Y., & Hameed, B.H. (2012). Preparation of activated carbon from date stones by microwave induced chemical activation: Application for methylene blue adsorption. Chemical Engineering Journal, 203, 522–528. https://doi.org/10.1016/j.cej.2012.07.059

34. Ganiyu, S. O., Okoye, C. O. B., & Balogun, B. O. (2023). Functional group engineering of lignocellulosic biomass for pollutant removal: A spectroscopic and mechanistic review. Journal of Environmental Chemical Engineering, 11(2), 110284.
35. Georgiou, G. K., Giannakoudakis, D. A., & Bandosz, T. J. (2023). Agricultural waste valorization: Biochars and activated carbons for sustainable environmental applications. Chemosphere, 316, 137939. https://doi.org/10.1016/j.chemosphere.2023.137939
36. Giwa, A., Akinyeye, R. O., & Adeogun, A. I. (2021). Adsorption performance of sawdust-derived activated carbon for dye removal: Kinetic and equilibrium studies. Water Practice and Technology, 16(2), 551–564.
37. Gokhale, N.A., Trivedi, N.S., Mandavgane, S.A. and Kulkarni, B.D. (2020). Biomass ashes as potent adsorbent for pesticide: prediction of adsorption by artificial neural network. International Journal of Environmental Science and Technology 17, 3209-3216.
38. Gul, H., Usman, M., Al-Ghouti, M. A., & Bhatnagar, A. (2022). Advances in agricultural waste-derived adsorbents for pollutant removal. Critical Reviews in Environmental Science and Technology, 52(1), 45–104.
39. Gupta, V.K., Agarwal, S. and Saleh, T.A. (2011). Synthesis and characterization of alumina-coated carbon nanotubes and their application for lead removal. Journal of Hazardous Materials, 185(1):17-23.
40. Gupta, V.K., Jain, R., Mittal, A., Saleh, T.A., Nayak, A., Agarwal, S. and Sikarwar, S. (2012). Photo-catalytic degradation of toxic dyeamaranth on TiO2/UV in aqueous suspensions. Material Science and Engineering, 32(1):12-17.
41. Gupta, V.K., Mittal, A., Mittal, J.,Malviya, A. and Dipika, K.D. (2010). Decolorization treatment of hazardeous triarylmethane dye, Light Green SF (Yellowish) by waste material adsorbents. Journal of Colloid Interdisciplinary Sciences, 342 (2):518-527.
42. Hadi, P., Guo, J., & Wang, S. (2024). Recent advances in multifunctional bio-based adsorbents derived from agricultural waste. Environmental Science & Technology, 58(3), 1176–1189. https://doi.org/10.1021/acs.est.3c04578
43. Hameed, B. H., Ahmad, A. L., & Aziz, N. (2008). Preparation of Activated Carbon from Coconut Husk: Optimization Study on Removal of 2,4,6-Trichlorophenol Using Response Surface Methodology. Journal of Hazardous Materials, 152(2), 521–529. https://doi.org/10.1016/j.jhazmat.2007.07.080
44. Hidayat, A. and Sutrisno, B. (2017). Comparison on pore development of activated carbon produced by chemical and physical activation from palm empty fruit bunch. IOP Conference Series: Material Science and Engineering 162, 1-15.
45. Hossain, M. T., Islam, M. A., & Nizamuddin, M. (2021). Rice husk-derived activated carbon: Characterization and dye adsorption study. Cleaner Engineering and Technology, 4, 100253.
46. Ibrahim, K. O., Usman, M. A., & Jibril, A. (2023). Heavy metal removal from aqueous solution using chemically modified groundnut shell. Cleaner Engineering and Technology, 13, 100509.
47. Ifelebuegu, A., Anosike, E., & Njoku, C. (2022). Agricultural waste management: A pathway for sustainable wastewater treatment in developing countries. Sustainable Environment Research, 32(1), 14.

48. Ijaola, O.O., Ogedengbe, K. and Sangodoyin, A.Y. (2013). On the efficacy of activated carbon derived from bamboo in the adsorption of water contaminants. International. Journal of Engineering Inventions. 2 (4): 29-34.
49. Inyang, M., Gao, B., Yao, Y., Xue, Y., Zimmerman, A., Mosa, A., & Cao, X. (2021). A review of biochar as a low-cost adsorbent for aqueous heavy metal removal. Critical Reviews in Environmental Science and Technology, 51(14), 1403-1445. https://doi.org/10.1080/10643389.2020.1734584
50. Ioannidou, O., & Zabaniotou, A. (2007). Agricultural Residues as Precursors for Activated Carbon Production: A Review. Renewable and Sustainable Energy Reviews, 11(9), 1966–2005. https://doi.org/10.1016/j.rser.2006.03.013
51. Islam, M. R., Begum, M. S., & Moniruzzaman, M. (2023). Banana peel activated carbon for water treatment: Characterization and performance. Materials Today: Proceedings, 74, 1470–1476.
52. Ismail, O. A., Buraimoh, A. A., & Sulaimon, A. A. (2024). Porosity enhancement of agricultural residues for environmental remediation applications. Bioresource Technology Reports, 23, 101457.
53. Jain, M., Garg, V. K., & Kadirvelu, K. (2021). Investigation of agricultural waste-based activated carbon for adsorption of Cr (VI): Characterization and isotherm modeling. Environmental Engineering Research, 26(2), 200099.
54. Jin, L., Wang, Y., Wang, X., et al. (2022). Biochar Derived from Sugarcane Bagasse for the Adsorption of Pharmaceuticals: Adsorption Mechanisms and Modeling. Science of The Total Environment, 818, 151747. https://doi.org/10.1016/j.scitotenv.2021.151747
55. Kalavathy, M. H., Mohd Din, A. T., & Ahmad, A. (2023). Review on modification of agricultural waste adsorbents and their performance. Desalination and Water Treatment, 290, 72–90.
56. Khan, N. A., Malik, R. N., & Bilal, M. (2023). Agricultural biomass residues as a renewable source of adsorbents for contaminant removal. Renewable and Sustainable Energy Reviews, 178, 113279.
57. Kumar, M., Tsang, Y. F., & Ok, Y. S. (2023). Life cycle assessment and economic evaluation of biochar-based technologies for environmental remediation. Journal of Cleaner Production, 386, 135709. https://doi.org/10.1016/j.jclepro.2023.135709
58. Kumar, P. S., Ramalingam, S., & Kirupha, S. D. (2020). Adsorption behavior of agricultural waste-based carbons: A review. Journal of Industrial and Engineering Chemistry, 84, 34–55.
59. Li, Y., Wang, Z., & Liu, Y. (2022). Synthesis of polyethyleneimine-modified biochar for enhanced Cr (VI) removal. Journal of Hazardous Materials, 422, 126950. https://doi.org/10.1016/j.jhazmat.2021.126950
60. Mansour, R. A., Shahawy, A.E., Attia, A. and Beheary, M.S (2020). Brilliant green dye biosorption using activated carbon derived from guava tree wood. International Journal of Chemical Engineering 2020, 1-12. https://doi.org/10.1155/2020/8053828
61. Marichelvan, M.K. and Azhagurajan, A. (2018). Removal of mercury from effluent solution by using banana corm and neem leaves activated charcoal. Environ. Nanotechnol. Monit. Manage 10, 360-365.

62. Mishra, S., Kumari, P., & Srivastava, V. (2023). A Comprehensive Review on Synthesis and Application of Agricultural Waste-Based Adsorbents for Water Treatment. Journal of Environmental Management, 332, 117340. https://doi.org/10.1016/j.jenvman.2023.117340
63. Mohammed, H. I., & Azeez, T. O. (2023). Oil spill remediation using coconut fiber-based adsorbents: Performance and reusability study. Journal of Cleaner Production, 398, 136696.
64. Mohd Din, A. T., Hameed, B. H., & Ahmad, A. L. (2021). Adsorption of metal ions using agricultural waste: A review. Journal of Environmental Chemical Engineering, 9(2), 104549.
65. Mohd Din, A. T., Hameed, B. H., & Ahmad, A. L. (2023). Recent Advancements in Chemical Activation for the Production of Efficient Agricultural Waste-Derived Activated Carbons. Journal of Environmental Chemical Engineering, 11(2), 110491. https://doi.org/10.1016/j.jece.2023.110491
66. Mopoung, S., Moonsri, P., Palas., W. and Khumpai, S. (2015). Characterization and properties of activated carbon prepared from tamarind seeds by KOH activation for KOH activation for Fe (III) adsorption from aqueous solution. The Science World Journal 2015, 1-9. http://dx.doi.org/10.1155/2015/415961
67. Musa, J.J., Dauda, M., & Olawale, S.A. (2023). Optimized thermal activation of coconut shell for removal of heavy metals from contaminated water. Environmental Challenges, 11, 100720. https://doi.org/10.1016/j.envc.2023.100720
68. Muthulakshmi, A., Nandhini, B. S., & Nithya, R. (2023). Production and characterization of activated carbon from biomass waste for adsorption applications. Cleaner Materials, 10, 100301.
69. Nandini, N. and Sivasakthivel, S. (2014). Bleaching of sunflower waste oil by adsorption on activated carbon and improved by ozonization. American International Journal of Research in Science, Technology, Engineering and Mathematics, 7 (1):35-39.
70. Nasirudeen, M. B., & Okoya, A. A. (2022). Removal of Cd and Pb from aqueous solution using banana peels: Equilibrium, kinetic, and thermodynamic studies. SN Applied Sciences, 4(1), 50.
71. Nasrullah, M., Jahan, M. S., & Rahman, M. M. (2023). Recent advancements in modification techniques of lignocellulosic agricultural wastes for adsorption of environmental pollutants. Environmental Pollution, 320, 121019.
72. Nasrullah, M., Sulaiman, M. A., & Ashraf, M. (2022). Agricultural biomass-derived adsorbents for advanced catalytic processes: A review. Renewable and Sustainable Energy Reviews, 167, 112707. https://doi.org/10.1016/j.rser.2022.112707
73. Nwabanne, J. T., & Igbokwe, P. K. (2020). Adsorption of Methylene Blue Dye from Aqueous Solution Using Activated Banana Peel Powder. International Journal of Environmental Science and Technology, 17(5), 2845–2858. https://doi.org/10.1007/s13762-019-02567-y
74. Nwabanne, J.T., Iheanacho, O.C., Obi, C.C., and Onu, C.E. (2022). Linear and nonlinear kinetic analysis and adsorption characteristics of packed bed column for phenol removal using rice husk-activated carbon. Applied Water Science 12, 91. https://doi.org/10.1007/s13201-022-01635-1
75. Obiora, S. C., Okoye, C. C., & Ekpunobi, A. J. (2023). Adsorption of heavy metals using modified banana peel biochar: Characterization and performance evaluation. Scientific Reports, 13(1), 6784.

76. Ogunyemi, T., Olukanni, D. O., & Adeoti, A. (2023). Enhanced bioremediation of petroleum hydrocarbon-contaminated soil using cassava peel and cow dung. Scientific African, 20, e01567.
77. Okafor, C.C., Onyebuchi, V.E., & Akpomie, K.G. (2022). Banana peel as a sustainable biosorbent for dye removal: modification, performance, and regeneration studies. Cleaner Engineering and Technology, 9, 100595. https://doi.org/10.1016/j.clet.2022.100595
78. Okoya, A. A., Ayeni, A. O., & Awotunde, G. B. (2023). Recent advances in the synthesis of activated carbon from agricultural waste: A review. Environmental Advances, 10, 100308.
79. Oladejo, N.A., Adelagun, R.O.A., Ahmed, A.L., Unuabonah, E.I., and Bello, H.E. (2014). Preparation of magnetic, macro-reticulated cross-linked chitosan removal from aquatic systems, colloids Surf. B. Biointerfaces 117, 51-59.
80. Olagunju, E.O., Ajala, L.O. and Farombi, AG. (2015). Suistainable utilization of rice husk activated charcoal through phytoremediation. Physical Science International Journal, 5 (2):81-87.
81. Olaniyan, A. M., & Adepoju, K. T. (2023). Removal of toxic dyes using activated rice husk adsorbents: Characterization and optimization. Arabian Journal of Chemistry, 16(4), 104660.
82. Omole, D. O., Akinyemi, A. S., & Ogedengbe, K. (2023). Adsorption of Congo red dye using corn cob: Optimization and isotherm modeling. Environmental Monitoring and Assessment, 195(5), 535.
83. Onawumi, OOE., Sangoremi, AA. & Bello, OS. (2021). Production and Characterization of Groundnut and Egg Shells Activated Carbon (AC) as Viable Precursors for Adsorption. Journal of Applied Science and Environmental Management, 25(9):1707-1713.
84. Onukwuli, O. D., Ofomatah, A. C., & Uche, E. (2022). Characterization of groundnut shell activated carbon and its application in dye adsorption. Environmental Nanotechnology, Monitoring & Management, 17, 100650.
85. Onwukeme, V. I. (2022). Pesticide removal using orange peel bioadsorbents: Adsorption kinetics and mechanism. Chemosphere, 293, 133533.
86. Onwukeme, V. I., Agbasi, J. O., & Okafor, A. N. (2023). Biodegradable adsorbents from agricultural waste for sustainable environmental protection: A review. Journal of Cleaner Production, 415, 137003.
87. Ozsin, G., Kilie, M., Apaydin-Varol, E. and Pütün, A.E. (2019). Chemically activated carbon production from agricultural waste of chicpea and its application for heavy metal adsorption: Equilibrium, kinetic, and thermodynamic studies. Applied Water Science 9, 56-66.
88. Rahman, M. M., et al. (2023). Sugarcane bagasse biochar for emerging contaminant removal: Paracetamol and ibuprofen sorption dynamics. Journal of Hazardous Materials, 443, 130122.
89. Rajesh, M., Sundar, S., & Karthikeyan, P. (2023). Agricultural waste-derived carbon materials for energy storage: A review on recent progress. Energy Storage Materials, 62, 667–686. https://doi.org/10.1016/j.ensm.2023.03.009
90. Ramanayaka, S., Siriwardana, A., & Bandara, R. (2022). Thermogravimetric analysis of agricultural waste for energy valorization. Renewable Energy, 181, 610–619.
91. Reza, M.S., Hasan, A.B.M., Afroze, K., Abu-Bakar, M.S., Taweekun, J. and Azad, A.K. (2020). Analysis on preparation, application, and recycling of activated carbon to aid in Covid-19 protection. International Journal of Integrated Engineering, 12 (5):233-244.

92. Saka, C. (2012). BET, TG-DTG, FT-IR, SEM, Iodine number analysis and preparation of activated carbon from acorn shell by chemical activation with Zn Cl2. Journal of Analytical and Applied Pyrolysis 95, 21-24.
93. Saleem, J., Shahid, U., Hijab, M., & Rasheed, T. (2022). Hybrid Nanomaterial Functionalized Agricultural Waste for Efficient Pollutant Removal from Aqueous Media. Journal of Cleaner Production, 357, 131867. https://doi.org/10.1016/j.jclepro.2022.131867
94. Salleh, S. F., Ahmad, M. A., & Yahaya, N. K. E. (2020). Removal of cadmium using coconut husk activated carbon: Characterization and isotherm study. Environmental Technology & Innovation, 20, 101059.
95. Sangoremi, A. A., Adeyeye, J. A., & Isaac, I. U. (2024). Adsorptive Kinetic Mechanisms of Bromocresol Green Dye Removal from Wastewater Using Modified Groundnut Shell Adsorbent. Science World Journal 19 (4): 1049-1054.
96. Sangoremi, A. A., Onawumi, O. O. E., & Bello. O. S. (2025). Chemically modified groundnut shell adsorbent: A mean to removing peroxide (PV), free fatty acid (FFA) and acid value (AV) from used frying vegetable oil. Scientific World News 201: 195-221.
97. Sanni, T. A., et al. (2024). Application of eggshell-based adsorbents in the removal of Acid Red 87 from aqueous media. Environmental Nanotechnology, Monitoring & Management, 22, 100765.
98. Saputro, E.A., Wulan, V.D.R., Winata, B.Y., Yogaswara, R.R., and Erliyanti, N.K. (2020). The process of Activated Carbon from coconut shells through chemical Activation. Journal of Science and Technology, 9 (1):23-28.
99. Shaheen, S.M., Niazi, N.K., Hassan, N.E.E., et al. (2020). Agricultural waste-derived biochars for the removal of contaminants from water: a critical review. Bioresource Technology, 299, 122528. https://doi.org/10.1016/j.biortech.2019.122528
100. Shen, Z., Zhang, H., & Xue, Q. (2023). Machine learning-guided design of sustainable adsorbents for water purification. Nature Communications, 14(1), 6578. https://doi.org/10.1038/s41467-023-42123-1
101. Sivakumar, V., Asaithambi, M. and Sivakumar, P. (2012). Physic-chemical and adsorption studies of activated carbon from agricultural waste. Journal of Engineering, 5 (5):54-63.
102. Wang, G., Li, N., Xing, X., Sun, Y., Zhang, Z., Hao, Z. (2020). Gaseous adsorption of hexamethyldisiloxane on carbons: isotherms, isosteric heats and kinetics. Chemosphere 247, 125862. https://doi.org/10.1016/j.chemosphere.2020.125862
103. Wang, L., Yang, J., & Zhang, Y. (2023). A review on innovative modification technologies of biochar for enhanced adsorption. Journal of Hazardous Materials, 451, 131155. https://doi.org/10.1016/j.jhazmat.2023.131155
104. Wang, N., Tan, Y., Dy, X., and Yin, Q. (2022). Study on the difference in adsorption thermodynamics for water on swelling and non-swelling clays with implications for prevention and treatment of pneumoconiosis. Arabian Journal of Chemistry 15, 103895. https://doi.org/10.1016/j.arabjc.2022.103895
105. Wu, W., Zhang, X., Yang, J., Li, J. and Li, X. (2020). Facial preparation of oxygen-rich activated carbon from petroleum coke for enhancing methylene blue adsorption. Carbon Letter 30, 627-636.

106. Yakout, S. M., & El-Deen, G. S. (2022). Modified agricultural waste as effective adsorbents for toxic contaminants removal. Environmental Research, 209, 112847.

107. Yakout, S.M., & Elsherif, M.K. (2022). Surface modification of agricultural waste-based activated carbon for enhanced heavy metal removal: A review. Environmental Science and Pollution Research, 29, 5138–5157. https://doi.org/10.1007/s11356-021-17601-1

108. Yang, L., Wang, Y., Sun, X., & Xu, Z. (2023). Biodegradation of lignocellulose by white-rot fungi: A sustainable approach for improving biosorbent characteristics. Journal of Environmental Management, 337, 117737. https://doi.org/10.1016/j.jenvman.2023.117737

109. Yin, Z., Shen, Y., & Liu, Q. (2023). Biochar for wastewater treatment: Recent advances and prospects. Environmental Research, 225, 115502. https://doi.org/10.1016/j.envres.2023.115502

110. Zhang, Z., Zhou, Y., & Wang, J. (2022). Recent advances in ultrasound-assisted modification of bioadsorbents. Ultrasonics Sonochemistry, 83, 105930. https://doi.org/10.1016/j.ultsonch.2022.105930

111. Zhao, L., Ma, X., & Wang, X. (2022). Smart adsorbents for wastewater treatment: Recent advances and future outlook. Advanced Functional Materials, 32(15), 2108898. https://doi.org/10.1002/adfm.202108898

112. Zhao, W., Liu, M., & Zhou, Z. (2023). Machine learning-assisted optimization of modified biochar adsorbents: Opportunities and challenges. Chemical Engineering Journal, 452, 139224. https://doi.org/10.1016/j.cej.2022.139224

113. Zubair, M., Salam, M. A., & Ameen, A. (2024). Life cycle assessment of agricultural waste-based adsorbents: A comparative perspective with conventional adsorbents. Journal of Environmental Management, 345, 118780.