

Agricultural Waste-Derived Bio-Adsorbents for Sustainable Water and Wastewater Treatment

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Abstract: *The increasing contamination of water resources by heavy metals, dyes, nutrients, pesticides, pharmaceuticals, and other pollutants has created a need for effective, affordable, and environmentally sustainable water-treatment technologies. Agricultural activities and food-processing industries generate substantial quantities of residues, including rice husk, sugarcane bagasse, wheat straw, corn cobs, coconut shells, fruit peels, and spent tea leaves. These materials are often discarded, burned, or used in low-value applications, despite their potential to serve as raw materials for bio-adsorbent production. Agricultural waste-derived bio-adsorbents offer a promising approach to wastewater treatment because their lignocellulosic composition, surface functional groups, and porous structures can support the removal of various dissolved contaminants. This review examines the development, modification, characterization, and environmental applications of agricultural waste-derived bio-adsorbents, considering research available up to 31 December 2022. The major categories of raw biomass adsorbents, chemically modified materials, biochar, and activated carbon are discussed. Important adsorption mechanisms, including ion exchange, surface complexation, electrostatic interactions, pore filling, and precipitation, are described along with the effects of pH, adsorbent dosage, contact time, initial pollutant concentration, temperature, and competing ions. The review also considers regeneration, safe disposal, economic feasibility, and the limitations of scaling laboratory findings to real wastewater systems. Published studies demonstrate that agricultural residues can be converted into useful treatment materials, but their practical application requires standardized testing, evaluation in complex wastewater matrices, and careful assessment of the entire material life cycle. Agricultural waste valorization therefore represents a promising contribution to circular-economy approaches for water and wastewater management..*

Keywords: Agricultural waste, bio-adsorbents, biosorption, wastewater treatment, biochar, activated carbon, heavy metals, dyes, sustainable water treatment, waste valorization.

I. INTRODUCTION

Water is essential for human health, agriculture, industrial development, and ecosystem functioning. However, rapid industrialization, population growth, urban expansion, and inadequate wastewater management have increased pressure on freshwater resources. Industrial effluents, agricultural runoff, municipal wastewater, and food-processing discharges may contain a wide range of pollutants, including toxic metals, synthetic dyes, excess nutrients, pesticides, pharmaceutical residues, and organic compounds.

Conventional wastewater-treatment methods include chemical precipitation, coagulation, ion exchange, membrane filtration, oxidation, and adsorption. Although these technologies can be effective, their cost, energy demand, chemical requirements, residual generation, and operational complexity may restrict their use in some locations. Adsorption has attracted substantial attention because it can be relatively simple to operate and can be adapted to different pollutants and treatment configurations.

Commercial activated carbon is a widely used adsorbent, but its preparation and replacement can be expensive for certain applications. This has encouraged research into alternative materials obtained from natural resources and waste streams. Agricultural residues are particularly promising because they are generated in large quantities and often

contain cellulose, hemicellulose, lignin, pectin, and other constituents with functional groups that interact with pollutants.

Mo et al. (2018) reviewed the preparation and application of agro-industrial waste-derived adsorbents, including techniques such as activation, carbonization, grafting, and nanostructuring. Their review emphasized that waste materials can be modified to improve their porosity and adsorption properties.

Similarly, Karić et al. (2022) examined agricultural waste as a biosorbent for inorganic and organic pollutants and highlighted the need for more realistic experiments using actual wastewater rather than only laboratory-prepared solutions.

The development of agricultural waste-derived bio-adsorbents can offer two related environmental benefits: it may reduce the quantity of agricultural residues requiring disposal, while creating useful materials for water purification. Nevertheless, a material's agricultural origin does not automatically make it safe, economical, or biodegradable under treatment conditions. Its preparation, performance, stability, and spent-material management must all be evaluated.

II. OBJECTIVES OF THE REVIEW

The principal objectives of this review are:

- To examine the potential of agricultural residues as raw materials for bio-adsorbent production.
- To describe the preparation and modification techniques used to improve adsorption performance.
- To discuss the physical and chemical properties relevant to pollutant removal.
- To explain the main mechanisms involved in adsorption and biosorption.
- To review applications in the removal of heavy metals, dyes, nutrients, pesticides, and other pollutants.
- To assess the factors affecting adsorption efficiency and the importance of regeneration.
- To identify economic, environmental, and technical challenges to practical implementation.
- To outline future research directions based on literature available up to 31 December 2022.

III. AGRICULTURAL WASTE AS A RESOURCE FOR BIO-ADSORBENT PRODUCTION

Agricultural waste includes residues generated during cultivation, harvesting, food processing, and the preparation of agricultural products. Depending on their composition and availability, these residues can be used directly as adsorbents or converted into more engineered materials.

The principal categories include:

- Crop residues, such as rice husk, rice straw, wheat straw, and corn cobs.
- Sugar-industry residues, including sugarcane bagasse.
- Fruit and vegetable wastes, including banana peels, orange peels, and other discarded plant tissues.
- Nut and seed residues, such as coconut shells and selected seed shells.
- Forestry and wood-processing residues, including sawdust and bark.
- Food-processing by-products, such as spent tea leaves and coffee grounds.

These materials differ in their lignin, cellulose, hemicellulose, pectin, ash, mineral, and extractive contents. Their suitability for adsorption depends on the type and accessibility of functional groups, surface area, pore structure, mechanical stability, and the chemistry of the target pollutant.

3.1 Cellulose, hemicellulose, and lignin

Cellulose is a structural polysaccharide containing hydroxyl groups that can participate in interactions with certain dissolved species. Hemicellulose contains a mixture of polysaccharides and may contribute additional hydroxyl and carboxyl groups. Lignin is a complex aromatic polymer containing oxygen-bearing functional groups.

These constituents can provide potential adsorption sites. However, raw agricultural biomass often has a relatively compact structure, and some binding sites may be inaccessible. Physical or chemical modification may expose additional sites or improve porosity.

3.2 Natural pectin and other plant components

Fruit peels and some vegetable residues contain pectin and other polysaccharides. Their carboxyl groups can interact with positively charged metal ions under suitable conditions. Plant-derived materials may also contain phenolic groups, proteins, waxes, and mineral components that influence their adsorption behaviour.

3.3 Mineral and ash components

Some agricultural residues contain silica, calcium, potassium, magnesium, and other inorganic constituents. These components may contribute to ion exchange, surface reactions, or precipitation during treatment. Their effects are material-specific: beneficial mineral phases may improve removal, while soluble constituents may alter water chemistry or introduce unwanted substances.

3.4 Why agricultural waste is attractive

Agricultural waste is a potential low-cost feedstock because it may be available locally, requires relatively limited processing for some applications, and can reduce dependence on virgin raw materials. Yet actual costs depend on collection, transport, seasonal availability, pretreatment, drying, grinding, activation, separation, and final disposal.

The most appropriate feedstock is therefore not necessarily the one with the highest reported laboratory adsorption capacity. A practical selection should consider local supply, target pollutants, treatment requirements, and whole-process costs.

IV. CLASSIFICATION OF AGRICULTURAL WASTE-DERIVED BIO-ADSORBENTS

Agricultural waste-derived adsorbents can be classified into four broad groups.

4.1 Raw biomass adsorbents

Raw biomass adsorbents are produced using basic operations such as washing, drying, grinding, and sieving. Examples include fruit peels, rice husk, sawdust, tea waste, and crop straw.

Their principal advantages are simplicity and low preparation requirements. Their limitations may include low mechanical strength, swelling, variable composition, leaching of dissolved organic compounds, and a relatively limited number of accessible binding sites.

4.2 Chemically modified bio-adsorbents

Chemical modification can alter the surface chemistry of agricultural biomass. Depending on the material and target pollutant, treatments may introduce, remove, or expose functional groups and change surface charge.

Possible approaches include acid treatment, alkaline treatment, oxidation, grafting, and functionalization with selected chemical groups. Modification can improve adsorption performance in certain systems, but it may increase production cost and create chemical residues that require control.

4.3 Biochar

Biochar is a carbon-rich material produced by thermally decomposing biomass under limited oxygen conditions. It is distinct from raw biomass because thermal treatment changes its carbon structure, porosity, mineral distribution, and surface chemistry.

The properties of biochar depend on the feedstock, pyrolysis temperature, heating rate, residence time, and post-treatment. Agricultural residues can provide suitable feedstocks, but each resulting biochar requires characterization.

Biochar has been investigated for the removal of heavy metals, organic pollutants, nutrients, and other contaminants. A 2022 review of biochar in wastewater treatment discussed the influence of feedstock and production conditions on adsorption performance, as well as the potential role of post-treatment.

4.4 Activated carbon from agricultural waste

Activated carbon is produced through carbonization and activation to develop a porous structure and suitable surface chemistry. Agricultural residues such as coconut shells, rice husk, bagasse, and other crop by-products can serve as precursors.

Activation can be physical, using suitable gases at elevated temperatures, or chemical, using activating agents followed by appropriate treatment. The choice affects pore development, surface functional groups, yield, energy use, and cost.

Activated carbon made from agricultural waste can be a useful alternative to some commercial materials, but the comparison must include activation efficiency, chemical consumption, adsorption performance, regeneration, and residual management.

V. PREPARATION AND DEVELOPMENT OF BIO-ADSORBENTS

The preparation process determines the physical and chemical characteristics of the final adsorbent. A suitable procedure depends on the raw material, the pollutant to be removed, the intended treatment method, and the resources available.

5.1 Collection and pretreatment

Agricultural residues should be collected from a known source and inspected for contamination. Materials containing soil, oils, pesticides, or other impurities may require additional pretreatment.

A typical preparation sequence includes:

Collection and sorting of the agricultural residue.

Washing with suitable water to remove soil and loose impurities.

Drying under controlled conditions.

Grinding and sieving to obtain a selected particle-size range.

Storing the material in clean, dry containers.

The washing procedure should be designed to minimize the introduction of contaminants and the generation of unnecessary wastewater. Drying temperature and duration should be reported because they can influence the properties of the biomass.

5.2 Physical modification

Physical methods include grinding, sieving, thermal treatment, and carbonization. Grinding reduces particle size and may increase accessible surface area, although very fine particles can be difficult to separate from treated water.

Carbonization changes the composition of the biomass and produces a carbon-rich material. Process conditions influence porosity, mineral phases, surface functional groups, and the final yield.

5.3 Chemical modification

Chemical modification can improve the performance of a selected adsorbent by changing its surface properties.

Common approaches include:

Acid treatment to remove certain mineral impurities or alter surface chemistry.

Alkali treatment to modify lignocellulosic structures.

Oxidation to introduce or increase oxygen-containing functional groups.

Grafting to attach selected functional groups or polymers.

Impregnation with selected minerals or other functional materials.

The suitability of any treatment must be demonstrated experimentally. Chemical modification is not always beneficial: it can reduce material yield, damage the structure, or introduce residues that require extensive washing.

5.4 Biochar production

Biochar production generally involves preparing the biomass, heating it under oxygen-limited conditions, cooling the product, and removing loose impurities as appropriate. The process temperature, residence time, heating rate, and feedstock characteristics should be documented.

The resulting biochar should be tested for properties such as pH, ash content, surface area, pore structure, elemental composition, and surface functional groups. A high production temperature may increase carbonization and alter porosity, but it may also reduce some oxygen-containing functional groups. Thus, the optimum conditions depend on the target contaminant and desired mechanism.

5.5 Activation and composite formation

Activation can enhance pore development, while composite formation may combine biomass-derived carbon with minerals, polymers, or other functional materials. Such approaches may improve separation, selectivity, or stability.

However, composites should be evaluated for the release of their components during treatment. If nanoscale materials or chemical additives are used, their potential release into treated water must be assessed.

VI. CHARACTERIZATION OF BIO-ADSORBENTS

Characterization is necessary to establish why a material performs as an adsorbent and whether it is suitable for practical treatment.

Characterization technique

Fourier-transform infrared spectroscopy (FTIR)

Scanning electron microscopy (SEM)

Energy-dispersive X-ray spectroscopy (EDS/EDX)

Brunauer–Emmett–Teller (BET) analysis

X-ray diffraction (XRD)

Point of zero charge (pH_{PZC}) measurement

Elemental analysis

Thermogravimetric analysis (TGA)

Inductively coupled plasma or atomic absorption analysis

Main purpose

Identifies functional groups and changes after adsorption

Examines surface morphology and visible structural features

Identifies elements present near the analyzed surface

Estimates specific surface area from gas adsorption measurements

Examines crystalline phases and mineral components

Helps interpret surface charge behaviour

Measures carbon, hydrogen, nitrogen, sulfur, and other relevant elements

Evaluates thermal stability and mass changes during heating

Measures dissolved metal concentrations in water samples

No single characterization method provides a complete description of an adsorbent. For example, FTIR may indicate changes in functional groups but does not, by itself, prove a unique adsorption mechanism. Likewise, BET surface area is not a direct measurement of adsorption capacity for a particular dissolved pollutant.

A strong study combines material characterization with controlled adsorption experiments, appropriate analytical measurements, and, where possible, evidence of the fate of the pollutant after treatment.

VII. MECHANISMS OF POLLUTANT REMOVAL

Agricultural waste-derived bio-adsorbents may remove contaminants through several mechanisms operating simultaneously. The relative importance of each mechanism depends on the material, target pollutant, and water chemistry.

7.1 Surface complexation

Surface complexation occurs when dissolved species interact chemically with functional groups on the adsorbent. Carboxyl, hydroxyl, amino, and other functional groups may bind certain metal ions.

The degree of interaction depends on pH, the chemical form of the pollutant, and the accessibility of the binding sites.

7.2 Ion exchange

Ion exchange occurs when ions in solution replace ions associated with the adsorbent. This mechanism may be important for materials containing exchangeable mineral ions or charged functional groups.

Competition from other dissolved ions can reduce selectivity. Therefore, experiments using actual wastewater or multi-component solutions are important for assessing performance.

7.3 Electrostatic interactions

Electrostatic attraction or repulsion depends on the surface charge of the adsorbent and the charge of the dissolved species. Since surface charge changes with pH, adsorption may vary considerably across different solution conditions.

This mechanism is particularly relevant to charged organic pollutants and some metal species, but it should not be assumed to dominate every system.

7.4 Pore filling and physical adsorption

Porous adsorbents can retain pollutants within accessible pores. Pore-size distribution, surface area, molecular size, and surface chemistry influence the extent of uptake.

For larger organic molecules, not all pores may be accessible. For metal ions, chemical interactions with surface groups or mineral phases may be more important than pore filling alone.

7.5 Precipitation and co-precipitation

Certain dissolved species can form insoluble compounds under suitable conditions. These compounds may be retained on or within the adsorbent. Some biochars contain mineral phases that alter solution chemistry and promote precipitation.

A decrease in dissolved concentration does not necessarily demonstrate adsorption alone. Appropriate controls are needed to distinguish adsorption from precipitation, filtration, or other removal processes.

7.6 Redox reactions

Some adsorbents can change the oxidation state of specific contaminants. Chromium is an important example because Cr(VI) and Cr(III) differ in toxicity and chemical behaviour.

Where redox transformations are relevant, studies should measure chemical speciation in addition to total contaminant concentration. This helps determine whether a pollutant was adsorbed, transformed, or both.

VIII. APPLICATIONS IN WATER AND WASTEWATER TREATMENT

8.1 Removal of heavy metals

Heavy metals and other toxic elements are important targets for agricultural waste-derived adsorbents. Potential contaminants include lead, cadmium, copper, nickel, zinc, chromium, and arsenic.

Fruit peels, rice husk, sawdust, biochar, and chemically modified biomass have been investigated for metal removal. Their performance depends on the chemical form of the metal, pH, competing ions, surface functional groups, and the presence of mineral phases.

For metals, the fate of the adsorbed contaminant must be considered carefully. The material may require regeneration, metal recovery, stabilization, or disposal as regulated waste. A high removal percentage alone is insufficient to establish environmental safety.

8.2 Removal of dyes

Synthetic dyes are used in textile, leather, paper, and other industries. Dye-containing wastewater may have high colour intensity and can contain additional chemicals that complicate treatment.

Agricultural waste-derived adsorbents have been investigated for the removal of dyes such as methylene blue and other model colourants. The adsorption mechanism depends on the dye's charge, molecular structure, solution pH, and the surface chemistry of the adsorbent.

Raw biomass may be sufficient for some dyes, whereas other applications may require carbonization or chemical modification. Studies should also measure whether the adsorbent releases coloured or dissolved organic substances into the treated water.

8.3 Removal of nutrients

Nitrogen- and phosphorus-containing compounds in wastewater can contribute to eutrophication when discharged into water bodies in excessive quantities.

Certain agricultural waste-derived materials, particularly appropriately prepared biochars and mineral-modified materials, may retain some nutrient species. However, nutrient removal depends strongly on the chemical form involved. For example, nitrate, ammonium, and phosphate behave differently in water.

A material should not be described as a universal nutrient adsorbent without evidence for the specific nutrient and experimental conditions.

8.4 Removal of pesticides and organic pollutants

Agricultural runoff and industrial wastewater may contain pesticides, phenolic compounds, and other organic pollutants. Biochar and activated carbon derived from agricultural residues may remove selected compounds through pore filling, hydrophobic interactions, and other surface interactions.

The effectiveness depends on the pollutant's molecular size, solubility, charge, and affinity for the adsorbent. Organic matter naturally present in wastewater may compete for adsorption sites or block pores.

8.5 Removal of pharmaceuticals and emerging contaminants

Pharmaceutical residues and other emerging contaminants may occur at low concentrations and can be difficult to remove using conventional biological treatment alone. Biochar and activated carbon derived from biomass have been studied for selected compounds.

Research in this area must distinguish laboratory performance from full-scale effectiveness. The presence of multiple contaminants, dissolved organic matter, and transformation products can influence the result.

8.6 Treatment of industrial and municipal wastewater

Agricultural waste-derived adsorbents may be used as part of a treatment train rather than as a stand-alone technology. For example, adsorption could follow sedimentation or biological treatment, depending on the target contaminants and water quality.

Karić et al. (2022) emphasized that studies with real wastewater are necessary because laboratory solutions do not reproduce the full complexity of environmental matrices.

IX. COMPARATIVE OVERVIEW OF AGRICULTURAL WASTE ADSORBENTS

The following table summarizes potential feedstocks and their typical areas of investigation. It is a qualitative guide, not a numerical ranking of performance.

Agricultural residue	Potential adsorbent form	Potential application	Key consideration
Rice husk	Raw biomass, silica-rich residue, biochar, activated carbon	Selected metals and organic pollutants	Ash and silica content affect performance
Rice straw	Raw biomass, biochar	Selected metals, dyes, and organic compounds	Composition and mineral content vary
Sugarcane bagasse	Raw biomass, modified biomass, biochar, activated carbon	Metals and dyes	Pretreatment may improve accessibility of binding sites
Banana peel	Raw or modified biomass, biochar	Selected metals and dyes	Swelling and leaching must be assessed
Orange and citrus peels	Raw biomass, modified biomass, carbonized adsorbent	Selected metals and dyes	Pectin and other soluble components may affect water quality
Coconut shell	Charcoal and activated carbon	Organic pollutants and selected metals	Carbonization and activation requirements
Corn cobs	Raw biomass, biochar, activated carbon	Dyes and selected dissolved contaminants	Performance depends on preparation conditions
Wheat straw	Raw biomass and biochar	Selected metals and organic pollutants	Seasonal availability and pretreatment
Sawdust	Raw or modified biomass, biochar	Metals and dyes	Wood species and extractives influence performance
Spent tea leaves	Raw or modified biomass	Selected metals and dyes	Material consistency and leaching require testing

Reviews available by 2022 document a broad range of agricultural residues used in bio-adsorbent development, including materials derived from fruits, vegetables, grains, seeds, and plant biomass. They also identify characterization, preparation, and contaminant-specific performance as important factors when selecting an adsorbent.

X. FACTORS AFFECTING ADSORPTION PERFORMANCE

The effectiveness of agricultural waste-derived bio-adsorbents depends on both the properties of the material and the conditions under which treatment is carried out.

10.1 Effect of pH

Solution pH influences surface charge, the ionization of functional groups, and the chemical form of dissolved contaminants. At low pH, hydrogen ions may compete with certain positively charged metal ions for binding sites. At higher pH, some surfaces become more negatively charged, which may promote metal binding.

However, changes in pH may also cause precipitation or changes in contaminant speciation. Therefore, the optimum pH must be established experimentally for each adsorbent–pollutant system.

10.2 Effect of adsorbent dosage

Increasing the adsorbent dosage often increases the total number of available binding sites and can improve percentage removal. However, adsorption capacity expressed in milligrams of pollutant per gram of adsorbent may decrease as dosage increases.

The best dosage is the one that achieves the required treatment performance at an acceptable material cost.

10.3 Effect of contact time

Adsorption may proceed rapidly at first, followed by a slower stage as accessible sites become occupied and mass transfer becomes more limiting. The time required to approach equilibrium varies among adsorbents and pollutants.

Contact time should be optimized using experimental measurements rather than assumed from studies involving different materials.

10.4 Effect of initial pollutant concentration

Initial concentration affects the driving force for mass transfer and the ratio of pollutant molecules to available binding sites. A higher concentration can increase the adsorption capacity per unit mass while decreasing the percentage removed.

Both measurements should be reported to allow meaningful comparison.

10.5 Effect of temperature

Temperature can influence diffusion, solubility, surface interactions, and adsorption equilibrium. Its effect depends on the individual system. Temperature-dependent experiments can help characterize the process, but thermodynamic conclusions should be based on suitable data and methods.

10.6 Effect of particle size

Smaller particles may expose more accessible surface area and reduce internal diffusion distances. However, very fine particles can be difficult to recover from treated water and may increase pressure drop in packed-bed systems.

10.7 Competing pollutants and dissolved salts

Real wastewater often contains several pollutants simultaneously. Competing ions, dissolved organic matter, and suspended solids may block adsorption sites, change surface charge, or alter contaminant speciation.

Testing in multi-component solutions and real wastewater is therefore necessary before practical application.

XI. ADSORPTION CAPACITY AND MATHEMATICAL MODELS

Adsorption studies commonly report percentage removal, adsorption capacity, and equilibrium behaviour. These parameters help evaluate material performance, although they must be interpreted alongside the experimental conditions.

11.1 Percentage removal

The percentage of pollutant removed can be calculated using:

$$R(\%) = \frac{C_0 - C_t}{C_0} \times 100$$

Where:

C_0 is the initial pollutant concentration.

C_t is the concentration after treatment time t .

R is the percentage removal.

11.2 Adsorption capacity

The adsorption capacity at time t is calculated as:

$$q_t = \frac{(C_0 - C_t)V}{m}$$

Where:

q_t is adsorption capacity, generally in mg/g.

V is the solution volume in litres.

m is the mass of adsorbent in grams.

At equilibrium, the terms C_t and q_t can be replaced by C_e and q_e .

11.3 Langmuir adsorption isotherm

The Langmuir model is often used to describe adsorption under an idealized assumption of finite, equivalent adsorption sites:

$$q_e = \frac{q_{\max} K_L C_e}{1 + K_L C_e}$$

Here, $q_{\max}$ represents the estimated maximum adsorption capacity and K_L is the Langmuir constant.

11.4 Freundlich adsorption isotherm

The Freundlich model is an empirical relationship often used to describe adsorption on heterogeneous surfaces:

$$q_e = K_F C_e^{1/n}$$

Here, K_F and n are empirical constants.

11.5 Adsorption kinetics

Pseudo-first-order and pseudo-second-order models are frequently used to examine how adsorption approaches equilibrium. Intraparticle diffusion models may also be useful for understanding transport limitations.

A good fit to a particular kinetic model does not, by itself, prove the underlying chemical mechanism. Model selection should consider the quality of the fit, experimental uncertainty, and physical plausibility.

XII. REGENERATION AND REUSE OF BIO-ADSORBENTS

Regeneration is important for evaluating the long-term sustainability and cost of an adsorbent. It may involve washing, acid or alkaline treatment, salt solutions, or other suitable desorption procedures.

Successful regeneration may recover part of the adsorption capacity and allow the material to be reused. Nevertheless, repeated cycles can damage the adsorbent, alter its functional groups, or reduce its mechanical strength.

Regeneration can also produce a concentrated stream containing the removed pollutants. This stream requires treatment or recovery and should not be discharged untreated.

A complete regeneration study should assess:

- Adsorption capacity after each cycle.
- Percentage of pollutant recovered during desorption.
- Chemical and energy consumption.
- Structural stability of the material.
- Changes in leaching behaviour.
- The final management of concentrated residues.

The practical advantage of reuse depends on the number of successful cycles and the associated costs. A material that performs well initially may not remain economical if it loses capacity quickly.

XIII. ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY

Agricultural waste-derived bio-adsorbents are consistent with circular-economy principles because they can convert low-value residues into materials for pollution control. However, their sustainability should be evaluated across the entire production and treatment process.

13.1 Environmental benefits

Potential benefits include:

Reduced disposal or open burning of agricultural residues.

Productive use of locally available biomass.

Reduced dependence on some virgin adsorbent materials.

Opportunities for rural waste valorization and local production.

Integration of waste management with water-pollution control.

These benefits depend on the alternative fate of the waste, the processing method, and the performance of the resulting material.

13.2 Economic considerations

A realistic cost analysis should include raw-material collection, transport, washing, drying, grinding, carbonization, activation, chemical modification, storage, and spent-material management.

The relevant measure is not simply the cost per kilogram of adsorbent. A more useful comparison is the cost per volume of water treated to the required final quality, including replacement, regeneration, energy, and residual handling.

13.3 Environmental risks

Potential risks include the release of dissolved organic matter, residual processing chemicals, ash constituents, or components of modified adsorbents. Metal-loaded adsorbents may also leach contaminants if disposed of improperly.

Before environmental deployment, the material should be tested for leaching, stability, and potential secondary contamination. The final water must be tested against the relevant regulatory requirements; adsorption alone does not guarantee drinking-water safety.

XIV. CHALLENGES AND RESEARCH GAPS

Despite encouraging findings, several issues must be resolved before agricultural waste-derived bio-adsorbents can be widely adopted.

14.1 Variability in raw materials. Agricultural residues differ by crop variety, growing conditions, harvesting methods, and processing history. Standardized preparation and characterization procedures are needed to improve reproducibility.

14.2 Inconsistent experimental conditions. Studies often use different pH values, concentrations, dosages, and contact times. Reported adsorption capacities cannot always be compared directly.

14.3 Limited testing with real wastewater. Synthetic solutions may not represent complex industrial or municipal wastewater. Studies should evaluate competing pollutants and actual water matrices.

14.4 Insufficient continuous-flow studies. Batch experiments are useful for initial screening, but fixed-bed column experiments are needed to assess breakthrough, service life, hydraulic performance, and scale-up.

14.5 Regeneration and residual management. More work is needed on repeated reuse, pollutant recovery, leaching, and safe disposal of spent adsorbents.

14.6 Scale-up and economic feasibility. Production conditions that work in a laboratory may not be economical at industrial scale. Pilot studies should evaluate yield, energy demand, chemical consumption, and treatment performance.

14.7 Selectivity and emerging contaminants. Research should investigate competitive adsorption, low-concentration contaminants, and the potential release of transformation products or adsorbent components.

14.8 Life-cycle assessment. A comprehensive evaluation should compare the environmental impact of waste-derived adsorbents with that of established treatment materials, accounting for processing, transport, regeneration, and disposal. These limitations are consistent with the reviews by Mo et al. (2018), Karić et al. (2022), and Aguilar-Rosero et al. (2022), which discuss the potential of agricultural waste-derived adsorbents and the need for improved preparation, characterization, and realistic application studies.

XV. FUTURE PERSPECTIVES

Future research should focus on improving the reliability, safety, and economic feasibility of agricultural waste-derived bio-adsorbents.

1. Locally available feedstocks: Identify residues that are abundant and inexpensive in the target region, with consistent composition and reliable year-round supply.
2. Targeted surface modification: Develop modifications for specific pollutants rather than assuming that one material will remove all contaminant classes equally well.
3. Standardized characterization: Use consistent methods to report surface area, functional groups, pore structure, pH, ash content, adsorption capacity, and leaching.
4. Real wastewater and pilot studies: Evaluate adsorbents in complex wastewater matrices and continuous-flow systems.
5. Regeneration and recovery: Develop methods that recover pollutants or produce manageable residues without excessive chemical or energy consumption.
6. Integrated treatment systems: Investigate how agricultural waste-derived adsorbents can complement filtration, biological treatment, precipitation, or other established processes.
7. Life-cycle and cost analysis: Assess whether the environmental and economic benefits remain after accounting for production, transport, treatment, and disposal.
8. Safe material design: Establish suitable testing procedures for chemical residues, leaching, and the stability of modified bio-adsorbents.

XVI. CONCLUSION

Agricultural waste-derived bio-adsorbents represent a promising approach to sustainable water and wastewater treatment. Materials such as rice husk, sugarcane bagasse, fruit peels, coconut shells, crop straw, sawdust, and spent tea leaves can be used directly or converted into modified biomass, biochar, and activated carbon.

Their adsorption performance depends on surface chemistry, pore structure, preparation method, target pollutant, solution pH, contact time, adsorbent dosage, and competing constituents. Characterization and controlled experimentation are essential for identifying the properties responsible for contaminant removal and for establishing whether the material is suitable for practical treatment.

The literature available up to 31 December 2022 demonstrates broad interest in agricultural waste valorization, but significant challenges remain in standardizing comparisons, validating performance in real wastewater, scaling up production, and managing spent adsorbents safely. Future research should combine adsorption experiments with regeneration studies, pilot-scale testing, life-cycle assessment, and realistic cost analysis.

In conclusion, agricultural waste-derived bio-adsorbents could contribute to circular-economy approaches by linking biomass utilization with water-pollution control. Their successful implementation will depend on demonstrating reliable treatment performance, economic feasibility, and environmental safety under practical operating conditions.

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