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SUSTAINABLE VALORIZATION OF PLANT BIOMASS WASTE FOR ENVIRONMENTAL APPLICATIONS

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ABSTRACT

The increasing generation of agricultural and plant-processing residues presents both an environmental challenge and an opportunity for sustainable resource recovery. Large quantities of fruit peels, seeds, leaves, husks, shells, stalks, straw and other lignocellulosic residues are generated annually from agricultural and food-processing activities. Improper disposal or open burning of these materials can contribute to environmental pollution and the loss of potentially valuable biomass resources. In recent years, the conversion of plant biomass waste into value-added materials has emerged as an important strategy within the circular bioeconomy. This review explores the potential of plant-derived agricultural residues as sustainable materials for environmental applications, particularly wastewater remediation. Plant biomass can be utilized directly as biosorbents or converted into modified adsorbents, biochar and activated carbon. Their cellulose, hemicellulose, lignin and associated functional groups provide active sites capable of interacting with dyes, heavy metals and other pollutants. Factors such as pH, adsorbent dosage, particle size, contact time, temperature and initial pollutant concentration influence the adsorption performance. Characterization techniques including Fourier-transform infrared spectroscopy, scanning electron microscopy, energy-dispersive X-ray analysis and surface-area measurements can provide information regarding surface morphology, elemental composition and functional groups. The valorization of plant residues offers a dual environmental benefit by reducing biomass waste while providing low-cost materials for pollution control. Future research should focus on regeneration, reusability, treatment of real wastewater, life-cycle assessment, scale-up and safe end-of-life management of pollutant-loaded biosorbents. The approach supports circular economy principles and contributes particularly to Sustainable Development Goals 6, 12 and 13.

Keywords: Plant Biomass, Agricultural Waste, Biosorbent, Biochar, Wastewater Treatment, Adsorption, Circular Bioeconomy, Sustainable Development

INTRODUCTION

Agricultural production and food-processing activities generate substantial quantities of plant-based residues. These residues include fruit and vegetable peels, seeds, shells, husks, stalks, straw, leaves, bagasse and other lignocellulosic materials. Although these materials are frequently considered waste, they contain cellulose, hemicellulose, lignin and a variety of functional groups that can provide useful physicochemical properties. Consequently, agricultural residues can be regarded as renewable raw materials rather than merely disposal problems.

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Conventional approaches to agricultural waste management include open burning, uncontrolled dumping, composting and disposal in landfills. Although some of these practices can be useful under appropriate conditions, inappropriate disposal or burning may contribute to air pollution, greenhouse gas emissions and loss of valuable biomass resources. Therefore, the conversion of agricultural residues into value-added products represents an important component of sustainable resource management.

At the same time, water pollution caused by industrialization, agriculture and urbanization has become a major environmental concern. Industrial effluents may contain dyes, heavy metals, phenolic compounds and other organic contaminants. Conventional wastewater treatment technologies can involve considerable costs, energy consumption and chemical requirements. Adsorption is widely investigated as a relatively simple approach for removing contaminants from aqueous systems.

Plant-based agricultural residues have attracted considerable attention as alternative adsorbent materials because they are abundant, renewable and inexpensive. Their surface contains functional groups such as hydroxyl and carboxyl groups that can participate in adsorption and other physicochemical interactions.

Thus, the conversion of plant biomass waste into environmental remediation materials represents a dual-benefit strategy: one waste stream is converted into a useful resource while another environmental problem, such as contaminated wastewater, is addressed. This concept is consistent with the principles of green chemistry, circular economy and sustainable biotechnology.

CONCEPT OF PLANT BIOMASS VALORIZATION

Plant biomass valorization refers to the conversion of agricultural and plant-processing residues into useful products with economic or environmental value. Instead of treating biomass residues solely as waste, the approach considers them as renewable feedstocks.

A simplified valorization pathway can be represented as:

Plant biomass waste → Collection → Cleaning → Drying → Size reduction → Pretreatment/modification → Characterization → Environmental application → Regeneration/reuse → Safe disposal

Depending on the nature of the biomass and intended application, several processing approaches can be adopted.

DIRECT UTILIZATION

Raw plant residues can be washed, dried, ground and sieved before being used directly as biosorbents. This approach has the advantage of being simple and requiring relatively low energy input.

CHEMICAL MODIFICATION

Chemical treatments can alter the surface chemistry of biomass and increase the availability of functional groups. Acid, alkali or other relatively mild modification strategies have been investigated for improving adsorption performance.

THERMAL CONVERSION

Plant residues can be thermally converted into biochar. Biochar production can increase surface area and modify surface chemistry, making the resulting material suitable for adsorption applications. Agricultural-waste-derived biochar has been investigated for treatment of domestic, industrial, agricultural and stormwater.

ACTIVATED CARBON PRODUCTION

Further activation of biomass-derived carbon can produce activated carbon with enhanced porosity and surface area. Plant biomass-derived activated carbons have been investigated for removal of contaminants including chromium, copper and zinc.

PLANT BIOMASS AS A BIOSORBENT

The adsorption potential of plant biomass is associated with its chemical composition and surface characteristics. Major structural components include:

- **Cellulose**
- **Hemicellulose**
- **Lignin**
- **Pectin**
- **Proteins**
- **Phenolic compounds**

- **Carboxyl and hydroxyl functional groups**

These components can provide binding sites for different pollutants.

For example, functional groups present on plant biomass may interact with metal ions through electrostatic attraction, ion exchange, complexation and surface binding. Organic pollutants and dyes can interact through electrostatic forces, hydrogen bonding, π–π interactions and other surface phenomena.

The exact mechanism depends on the biomass, pollutant and environmental conditions.

MAJOR PLANT-BASED WASTE MATERIALS

A wide range of plant residues can potentially be explored as biosorbent materials.

Plant biomass waste	Potential application
Rice husk	Heavy metals, dyes
Coconut shell/husk	Heavy metals, dyes
Banana peel	Dyes, metal ions
Citrus peel	Dyes, metal ions
Sugarcane bagasse	Dyes, metal ions
Groundnut shell	Metal ions
Corn cob	Dyes and heavy metals
Fruit seeds	Organic and inorganic pollutants
Tea/plant processing residues	Dyes and metal ions
Leaves and agricultural residues	General biosorption applications

Several agricultural by-products, including rice residues, citrus peel, banana peel, coconut materials, sugarcane bagasse and cereal residues, have been investigated as low-cost biosorbents.

ENVIRONMENTAL APPLICATIONS

REMOVAL OF DYES FROM WASTEWATER

Synthetic dyes are widely used in textile, food, pharmaceutical and other industries. Their release into water bodies can reduce light penetration and adversely affect aquatic ecosystems.

Plant-derived biosorbents can provide an inexpensive alternative for dye removal. Agricultural wastes have been investigated for the adsorption of both cationic and anionic dyes. Modification of biomass can further improve its affinity toward specific dye classes.

One important model pollutant frequently investigated in adsorption studies is methylene blue. Agricultural waste-derived materials have been extensively explored for its removal from aqueous systems.

REMOVAL OF HEAVY METALS

Heavy metals such as:

- **Lead (Pb)**
- **Cadmium (Cd)**
- **Chromium (Cr)**
- **Copper (Cu)**
- **Zinc (Zn)**
- **Nickel (Ni)**

can enter aquatic systems through industrial and agricultural activities.

Unlike many organic pollutants, heavy metals cannot be biologically degraded. Therefore, their removal and subsequent safe management are essential.

Agricultural waste-based adsorbents have demonstrated potential for removing heavy metal ions from aqueous systems. Adsorption performance is influenced by parameters including pH, adsorbent dosage, pollutant concentration, contact time and temperature.

REMOVAL OF EMERGING POLLUTANTS

Recent research has expanded beyond conventional dyes and metals to include emerging contaminants. Agricultural-waste-derived biosorbents have been investigated for the removal of various organic pollutants and other contaminants from water.

This creates opportunities for developing multifunctional plant-derived materials capable of treating complex wastewater.

PROPOSED METHODOLOGY FOR SUSTAINABLE PLANT-BASED BIOSORBENT DEVELOPMENT

A generalized experimental workflow is proposed below.

Step 1: Selection of plant biomass

Locally abundant agricultural or food-processing residues should be selected based on:

- **Availability**
- **Renewable nature**
- **Low cost**
- **Ease of collection**
- **Lignocellulosic composition**
- **Potential environmental impact of disposal**

Step 2: Collection and preprocessing

The collected biomass should be washed thoroughly to remove soil, dust and other contaminants. The material can then be dried under controlled conditions and converted into smaller particles using suitable grinding equipment.

Step 3: Size fractionation

The dried biomass can be sieved into defined particle-size ranges. Particle size is an important parameter because smaller particles generally provide greater accessible surface area.

Step 4: Modification

The raw biomass can be compared with one or more modified forms.

For example:

Raw biomass → Alkali-treated biomass → Thermally treated biomass → Biochar

The use of chemical modification should be minimized where possible to maintain the sustainability advantages of the process.

Step 5: Characterization

The prepared biosorbent can be characterized using:

FTIR:

To identify major functional groups.

SEM:

To examine surface morphology and structural changes.

EDX/EDS:

To determine elemental composition.

BET analysis:

To estimate surface area and pore characteristics.

pH at point of zero charge (pHpzc):

To understand surface charge characteristics.

These techniques are commonly used to evaluate biomass-based adsorbents and understand their adsorption behavior.

BATCH ADSORPTION STUDIES

The adsorption performance of the prepared biomass can be evaluated using batch experiments.

A typical experimental design can investigate the effect of:

1) Adsorbent dosage
2) Initial pollutant concentration
3) Contact time
4) Solution pH
5) Temperature
6) Particle size

After treatment, the residual pollutant concentration can be measured using an appropriate analytical technique.

For dyes, UV–Visible spectrophotometry can be used when the selected dye and analytical wavelength are appropriate.

For metal ions, techniques such as atomic absorption spectroscopy, ICP-OES or suitable validated colorimetric methods can be considered depending on available instrumentation.

The percentage removal can be calculated as:

Removal (%)=C0−CeC0×100\text{Removal (\%)} = \frac{C_0-C_e}{C_0}\times100

where:

$\mathbf{C_0}$ = initial pollutant concentration

$\mathbf{C_e}$ = equilibrium pollutant concentration

The adsorption capacity can be calculated as:

qe=(C0−Ce)Vmq_e = \frac{(C_0-C_e)V}{m}

where:

$\mathbf{q_e}$ = adsorption capacity

$\mathbf{C_0}$ = initial concentration

$\mathbf{C_e}$ = equilibrium concentration

V = volume of solution

m = mass of biosorbent

ADSORPTION KINETICS AND ISOTHERMS

Understanding adsorption kinetics is essential for evaluating the practical performance of plant-derived biosorbents.

Common kinetic models include:

- Pseudo-first-order model
- Pseudo-second-order model
- Elovich model
- Intraparticle diffusion model

Adsorption equilibrium can be evaluated using models such as:

- Langmuir isotherm
- Freundlich isotherm
- Temkin isotherm

The Langmuir model assumes adsorption onto a relatively homogeneous surface, whereas the Freundlich model is generally associated with heterogeneous adsorption surfaces.

Agricultural-waste adsorption studies have frequently employed Langmuir and Freundlich models to characterize adsorption behavior.

MECHANISMS OF POLLUTANT REMOVAL

The adsorption of pollutants onto plant-derived materials may involve multiple mechanisms.

ELECTROSTATIC ATTRACTION

Charged pollutant species can interact with oppositely charged functional groups on the biosorbent surface.

ION EXCHANGE

Metal ions present in solution may exchange with ions associated with functional groups on the biomass.

COMPLEXATION

Metal ions can form complexes with oxygen-containing or other functional groups present on the biomass.

HYDROGEN BONDING

Organic pollutants can interact with hydroxyl and other polar groups through hydrogen bonding.

PHYSICAL ADSORPTION

Van der Waals interactions and pore filling may contribute to pollutant uptake.

Π–Π INTERACTIONS

Aromatic pollutants may interact with aromatic structures present in lignin-derived or carbonized biomass.

In many practical systems, more than one mechanism may operate simultaneously.

SUSTAINABILITY AND CIRCULAR BIOECONOMY PERSPECTIVE

The major strength of plant biomass valorization lies in its ability to connect **waste management with environmental remediation.**

The conventional linear model can be represented as:

Agricultural production → Biomass residue → Disposal/burning → Environmental burden

A circular model instead follows:

Agricultural production → Biomass residue → Processing → Biosorbent/Biochar → Wastewater treatment → Regeneration/reuse → Resource recovery

This approach provides several potential benefits:

- Reduction in agricultural waste
- Reduced dependence on expensive commercial adsorbents
- Utilization of renewable resources
- Development of low-cost remediation technologies
- Reduction in open burning and uncontrolled disposal
- Potential local employment and rural value creation
- Contribution to circular bioeconomy development

Reviews of agricultural-waste biosorbents emphasize that using locally available biomass can simultaneously address solid-waste management and water pollution.

REGENERATION AND REUSABILITY

A major consideration for practical application is whether the biosorbent can be regenerated and reused.

A material that exhibits high pollutant removal during a single laboratory experiment may not necessarily be economically or environmentally sustainable if it cannot be reused.

Therefore, future studies should investigate:

Adsorption → Desorption → Washing/Regeneration → Reuse → Performance evaluation

The adsorption capacity after each cycle can be compared with the initial adsorption capacity.

Regeneration studies are particularly important because they influence the overall material consumption, operational cost and environmental footprint of the process.

Recent sustainability-focused research has emphasized the need to consider regeneration, repeated use and safe end-of-life management of heavy-metal-loaded biosorbents rather than evaluating adsorption efficiency alone.

CHALLENGES AND RESEARCH GAPS

Although plant-based biosorbents have significant potential, several challenges remain.

VARIATION IN BIOMASS COMPOSITION

The chemical composition of plant residues can vary according to:

- Plant species
- Cultivation conditions
- Soil characteristics
- Geographic location
- Plant maturity
- Processing conditions

This variation can influence adsorption performance.

LABORATORY-TO-FIELD TRANSLATION

A major limitation of existing research is that many studies are performed using synthetic wastewater under controlled laboratory conditions. More studies using real industrial wastewater are required.

REGENERATION

The number of effective adsorption–desorption cycles needs to be established.

POLLUTANT-LOADED BIOMASS

Once the biosorbent has captured heavy metals or other hazardous pollutants, its disposal must be carefully managed.

SCALE-UP

Large-scale production requires evaluation of:

- Processing cost
- Energy requirements
- Water consumption
- Chemical requirements
- Transportation
- Storage
- Reactor design

LIFE-CYCLE ASSESSMENT

Future research should compare plant-derived adsorbents with conventional activated carbon using life-cycle assessment, considering raw-material acquisition, processing, transportation, application, regeneration and disposal.

PROPOSED SUSTAINABLE RESEARCH MODEL

A practical research framework can therefore be developed as follows:

Locally available plant waste

↓

Preprocessing and characterization

↓

Development of raw/modified biosorbent

↓

Biochar or activated carbon production

↓

Physicochemical characterization

↓

Pollutant removal studies

↓

Optimization of adsorption parameters

↓

Kinetic and isotherm analysis

↓

Regeneration and reusability

↓

Real wastewater validation

↓

Life-cycle and economic assessment

↓

Prototype development

This integrated approach would move the research beyond a simple laboratory adsorption experiment toward a more comprehensive sustainable technology.

SUSTAINABLE DEVELOPMENT GOALS

Plant biomass valorization for wastewater remediation has direct relevance to several United Nations Sustainable Development Goals.

SDG 6 – Clean Water and Sanitation

Plant-based adsorbents can contribute to the development of affordable approaches for wastewater treatment and water-quality improvement.

SDG 12 – Responsible Consumption and Production

The conversion of agricultural residues into value-added environmental products supports resource efficiency and waste reduction.

SDG 13 – Climate Action

Reducing open burning and promoting biomass utilization can contribute to lower environmental impacts, although the actual climate benefit should be confirmed through life-cycle assessment.

SDG 9 – Industry, Innovation and Infrastructure

Development of biomass-based treatment technologies can encourage sustainable technological innovation.

SDG 15 – Life on Land

Improved management of agricultural residues can help reduce environmental pressures associated with inappropriate waste disposal.

FUTURE PERSPECTIVES

Future research should shift from demonstrating adsorption capacity under ideal laboratory conditions toward developing complete sustainable treatment systems.

Particular attention should be given to:

1) Selection of locally abundant plant residues.
2) Green and low-energy modification methods.
3) Development of multifunctional biosorbents.
4) Treatment of real industrial wastewater.
5) Continuous-flow adsorption systems.

6) Regeneration and multiple-use studies.
7) Recovery of valuable metals from spent adsorbents.
8) Safe management of exhausted biosorbents.
9) Life-cycle assessment.
10) Techno-economic analysis.
11) Pilot-scale validation.
12) Integration with existing wastewater treatment systems.

The combination of biotechnology, green chemistry, materials science and environmental engineering could significantly improve the practical applicability of plant-derived environmental materials.

CONCLUSION

Plant biomass waste should not be considered merely as an agricultural disposal problem but as a renewable resource with significant potential for environmental applications. Fruit peels, seeds, husks, shells, leaves, stalks and other agricultural residues contain functional components that can support the development of biosorbents, biochar and activated carbon. These materials have demonstrated potential for the removal of dyes, heavy metals and other pollutants from aqueous systems.

The valorization of plant residues provides an opportunity to simultaneously address agricultural waste generation and water pollution. However, adsorption capacity alone should not be considered sufficient evidence of sustainability. Regeneration, reusability, treatment of real wastewater, energy requirements, economic feasibility and end-of-life management must also be incorporated into future research.

A complete waste-to-resource approach, supported by circular bioeconomy principles, could transform locally available plant residues into useful environmental remediation materials. Such approaches have the potential to promote low-cost pollution control, resource recovery and sustainable technological innovation while contributing to the broader objectives of the Sustainable Development Goals.

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