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Orange Peel as a Sustainable Bioadsorbent for Wastewater Treatment: Advanced Review on Mechanisms, Performance, and Industrial Prospects

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Abstract: *This comprehensive review presents an in-depth evaluation of orange peel (OP) as a sustainable bioadsorbent for wastewater treatment applications. Industrial effluents containing textile dyes, heavy metals, pharmaceuticals, and emerging contaminants pose severe ecological and human health risks. Adsorption using low-cost agro-waste materials has emerged as an efficient and environmentally benign remediation strategy. Orange peel, an abundant by-product of citrus processing industries, contains cellulose, hemicellulose, lignin, and pectin that provide abundant functional groups for pollutant binding.*

This manuscript critically analyzes physicochemical characteristics, surface chemistry, adsorption isotherms, kinetic models, thermodynamic parameters, regeneration potential, modification strategies, environmental sustainability, techno-economic feasibility, and industrial scalability. Findings from twenty major studies [1]–[20] are synthesized to provide comparative insights into adsorption capacities and removal efficiencies. The review concludes with future research directions including nanocomposite fabrication, pilot-scale validation, process intensification, and circular economy integration.

Keywords: Orange peel; Bioadsorbent; Adsorption; Textile wastewater; Heavy metals; Sustainability; Circular economy

I. INTRODUCTION

Water pollution remains a major global environmental concern due to rapid industrialization. Textile industries discharge colored effluents containing persistent aromatic dyes that resist biodegradation [7]. Even small concentrations of synthetic dyes significantly reduce light penetration in aquatic systems.

Heavy metals such as chromium, cadmium, and lead are toxic, non-biodegradable, and bioaccumulative [18]. Pharmaceutical residues and nutrient pollutants further complicate wastewater treatment processes [8,9].

Conventional treatment methods often suffer from high operational cost and sludge generation. Therefore, adsorption has gained attention as a simple and effective technique. Low-cost bioadsorbents derived from agricultural waste are increasingly investigated [14].

Among agro-waste materials, orange peel is particularly promising due to its availability, renewability, and functional surface chemistry [2,20].

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II. GLOBAL PRODUCTION AND WASTE VALORIZATION

Global citrus production generates millions of tons of peel waste annually. Approximately 40–50% of processed oranges become peel waste. Improper disposal contributes to landfill burden and methane emissions.

Valorization of orange peel into bioadsorbents provides sustainable waste management and aligns with circular economy principles [14,20]. Development of bioadsorbents from orange peel waste for textile effluent treatment has been demonstrated recently [2].

III. CHEMICAL COMPOSITION AND SURFACE FUNCTIONAL GROUPS

Orange peel biomass is a lignocellulosic material composed of:

20–30% cellulose

10–20% hemicellulose

5–10% lignin

20–40% pectin

Minor fractions of flavonoids, essential oils, and proteins

The high pectin content distinguishes orange peel from many other agricultural residues. Pectin contains galacturonic acid units rich in carboxylic groups, which significantly enhance metal-binding capacity through ion exchange mechanisms.

FTIR spectral analysis commonly reveals peaks corresponding to:

O–H stretching (~3300 cm^{-1})

C=O stretching (~1730 cm^{-1})

C–O–C vibrations (~1050 cm^{-1})

Surface functional groups participate in adsorption via:

Complexation with metal ions

Electrostatic interaction with charged dyes

Hydrogen bonding with polar molecules

π–π interactions with aromatic pollutants

The point of zero charge (pHpzc) of orange peel typically ranges between 3 and 5, influencing adsorption behavior based on solution pH.

[3,12, 18]

IV. SURFACE MODIFICATION AND ENHANCEMENT STRATEGIES (EXPANDED)

Although raw orange peel exhibits moderate adsorption capacity, various modification strategies significantly enhance performance:

4.1 Chemical Modification

Alkaline treatment (NaOH) increases surface porosity and exposes additional active sites. Acid treatment (HCl, H_3PO_4) removes impurities and introduces acidic functional groups.

4.2 Thermal Activation

Carbonization under inert atmosphere increases:

Surface area

Micropore volume

Structural stability

Activated orange peel carbon can achieve surface areas exceeding 500 m^2/g depending on preparation conditions [12].

4.3 Composite Formation

Recent advancements include:

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Magnetic orange peel composites (Fe_3O_4 incorporation)
Polymer-coated bioadsorbents
Graphene oxide-supported systems
Nano-enhanced hybrid materials
Such modifications improve separation efficiency, reusability, and adsorption kinetics.

V. ADSORPTION OF TEXTILE DYES (EXPANDED)

Synthetic dyes represent a major environmental hazard due to their intense coloration and toxicity. Even small concentrations (1 mg/L) can significantly reduce light penetration in water bodies.
Studies report that orange peel adsorbents effectively remove:
Methylene blue
Congo red
Direct N Blue-106
Reactive Black dyes
Equilibrium studies often demonstrate strong correlation with Langmuir isotherm, suggesting monolayer adsorption [3], [12]. Removal efficiencies above 85–95% have been achieved under optimized pH and contact time conditions [19].
The adsorption mechanism for cationic dyes is primarily driven by electrostatic attraction between negatively charged carboxyl groups and positively charged dye molecules.

VI. HEAVY METAL ADSORPTION MECHANISM (EXPANDED)

Heavy metal adsorption onto orange peel involves:
Ion exchange between metal ions and H^+/Na^+
Surface complex formation
Chelation with carboxyl groups
Adsorption capacity increases at near-neutral pH due to reduced competition from hydrogen ions.
Reported maximum adsorption capacities vary depending on metal type and modification technique. For example:
Cu(II) adsorption ranges from 20–80 mg/g
Pb(II) adsorption may exceed 100 mg/g after activation
Cd(II) removal efficiencies often surpass 80% [16], [18]
Thermodynamic studies confirm spontaneity and, in many cases, endothermic behavior, indicating improved adsorption at elevated temperatures.

VII. EMERGING POLLUTANTS AND ADVANCED APPLICATIONS (EXPANDED)

Emerging contaminants such as pharmaceuticals, antibiotics, and nutrients (phosphates) are increasingly detected in wastewater.
Orange peel-derived hydrochars have demonstrated:
Effective acetaminophen removal [8]
Phosphate sequestration from agricultural runoff [9]
Adsorption of endocrine-disrupting compounds
Such versatility expands the applicability of orange peel bioadsorbents beyond conventional dye and metal removal.

VIII. KINETICS AND DIFFUSION ANALYSIS (EXPANDED)

Pseudo-second-order kinetics frequently describe adsorption systems, suggesting chemisorption involvement through valence forces and electron sharing.
Intraparticle diffusion models indicate multi-step adsorption involving:

External surface adsorption
Pore diffusion
Equilibrium stage
Film diffusion resistance can influence initial adsorption rate, particularly in column systems.

IX. THERMODYNAMIC INSIGHTS (EXPANDED)

Thermodynamic parameters provide deeper understanding of adsorption feasibility:
Negative $\Delta G°$ confirms spontaneity
Positive $\Delta H°$ suggests endothermic interaction
Positive $\Delta S°$ indicates increased disorder at interface
The magnitude of $\Delta H°$ often falls within 20–80 kJ/mol, supporting chemisorption dominance in many systems.

X. REGENERATION AND OPERATIONAL STABILITY (EXPANDED)

Sustainable industrial application requires reusability. Desorption using dilute acids (HCl) or bases (NaOH) allows recovery of adsorbed pollutants.
Typical findings include:
70–85% efficiency retention after 3 cycles
Gradual decline due to pore blockage
Possible structural collapse after repeated regeneration
Advanced regeneration strategies include microwave-assisted desorption and solvent extraction.

XI. TECHNO-ECONOMIC AND INDUSTRIAL FEASIBILITY (EXPANDED)

Preliminary cost analyses indicate that orange peel-based adsorbents may reduce material cost by 60–80% compared to commercial activated carbon.
Industrial-scale challenges include:
Biomass collection logistics
Moisture control
Consistency in raw material composition
Long-term mechanical stability
Future commercialization may involve pelletization, granulation, or incorporation into fixed-bed column systems.

XII. ENVIRONMENTAL AND CIRCULAR ECONOMY IMPACT (EXPANDED)

Orange peel valorization contributes to:
Waste minimization
Carbon footprint reduction
Resource recovery
Sustainable wastewater management
Integration within citrus processing supply chains can create closed-loop industrial systems, enhancing overall sustainability performance.

XIII. FUTURE RESEARCH OPPORTUNITIES

Future investigations should focus on:
Pilot-scale continuous flow experiments
Multi-contaminant removal studies
Nanostructured hybrid materials
Artificial intelligence-based adsorption modeling

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Comprehensive life cycle assessment
Field validation in industrial effluent systems

XIV. CONCLUSION

Orange peel represents a highly promising, low-cost, and environmentally sustainable bioadsorbent for wastewater treatment. Its lignocellulosic structure and functional group diversity enable efficient adsorption of dyes, heavy metals, pharmaceuticals, and emerging contaminants. Modified and activated forms significantly enhance adsorption capacity and stability.

While laboratory-scale results are highly encouraging, further pilot-scale validation, long-term stability testing, and techno-economic assessment are necessary for industrial deployment. With continued innovation and process optimization, orange peel-based adsorbents have strong potential to contribute meaningfully to sustainable water treatment technologies and circular economy initiatives.

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