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BIO-BASED AND LOW-COST ADSORBENTS FOR THE REMOVAL OF CRYSTAL VIOLET DYE FROM WASTEWATER: A COMPREHENSIVE REVIEW

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ABSTRACT:
Crystal Violet (CV), a synthetic cationic dye extensively used in textile and printing industries, poses environmental and health risks due to its toxicity and persistence in aquatic systems. Conventional dye removal methods are often costly and inefficient. This review provides an in-depth analysis of various bio-based and low-cost adsorbents used for CV dye removal from wastewater. It discusses adsorption mechanisms, factors influencing adsorption efficiency, kinetic and isotherm models, and comparative performance evaluations, based on literature published till now. The review supports the development of sustainable and cost-effective wastewater treatment solutions.

Keywords:
Crystal Violet, bio-based adsorbents, low-cost materials, adsorption, wastewater treatment,

1. INTRODUCTION

With the rapid advancement of industries such as textiles, paper manufacturing, and dyeing, there has been a significant rise in the release of dye-contaminated wastewater. Among various synthetic dyes, Crystal Violet (CV) is widely used due to its vibrant colour and application flexibility. However, it is chemically stable, non-biodegradable, and remains in water bodies for extended periods, causing environmental harm and health hazards. Traditional dye removal methods like chemical oxidation, coagulation-flocculation, and membrane filtration, though effective, come with high operational costs and the challenge of secondary pollution. This necessitates the exploration of alternative techniques that are cost-effective and environmentally friendly. Adsorption has gained attention as a promising technique for dye removal from wastewater because of its simplicity, economic feasibility, and efficiency. Particularly, bio-based and low-cost adsorbents sourced from agricultural residues, plant biomass, and industrial by-products have demonstrated excellent potential. These materials are naturally abundant, biodegradable, and rich in functional groups that can interact with dye molecules. This review focuses on such bio-adsorbents, evaluating their performance in removing Crystal Violet from wastewater based on studies published till now.

2. AGRICULTURAL WASTE-DERIVED ADSORBENTS:

Agricultural residues offer a plentiful and cost-effective source of raw materials for adsorbent preparation. These by-products—such as rice husks, wheat straw, coconut shells, and sawdust—are often discarded or underutilized. However, they possess an internal structure made up of lignocellulose components, including cellulose, hemicellulose, and lignin.

These biopolymers are rich in functional groups such as hydroxyl, carboxyl, and methoxy, which can form strong bonds with dye molecules through various mechanisms like hydrogen bonding, electrostatic interaction, and Van der Waals forces. Due to their natural porosity and surface area, these materials can be modified or used in their raw form to enhance dye adsorption.

The use of agricultural waste not only contributes to wastewater treatment but also promotes sustainability by turning waste into value-added products. Numerous studies have demonstrated the efficiency of such materials in adsorbing Crystal Violet dye from aqueous solutions, making them a viable solution for dye pollution control.

2.1 Rice Husk as an Adsorbent for Crystal Violet Removal

Rice husk, a major by-product of rice milling, has emerged as a highly effective and low-cost adsorbent for the removal of Crystal Violet from wastewater. Rich in lignocellulosic compounds, rice husk contains a significant

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amount of silica, cellulose, and hemicellulose, providing a large surface area and abundant functional groups for dye binding (1,2).Studies till now have demonstrated that both raw and chemically modified rice husk show considerable adsorption capacities for CV. Acid or base treatments can enhance the porosity and availability of active sites, thus improving adsorption efficiency (3,4).The mechanisms involved include electrostatic attraction, hydrogen bonding, and π-π interactions between the dye molecules and rice husk components (5,6).In addition to its high adsorption potential, rice husk is renewable, widely available, and inexpensive, making it an ideal candidate for large-scale wastewater treatment. Its application not only aids in reducing dye contamination in water bodies but also adds value to an agricultural waste product, supporting environmental sustainability (7, 8).Key parameters influencing its performance include pH, initial dye concentration, contact time, and temperature. Isotherm studies—especially Langmuir and Freundlich models—have been used to describe the equilibrium behavior of CV on rice husk, while kinetic models like pseudo-second-order equations effectively explain the adsorption rate (9,10).Overall, rice husk presents a promising, eco-friendly alternative for the removal of Crystal Violet, offering both environmental and economic advantages (11).

2.2. Coconut Coir Dust as an Adsorbent for Crystal Violet Removal

Coconut coir dust, an abundant by-product from coconut processing, has emerged as an effective, low-cost adsorbent for removing Crystal Violet (CV) dye from wastewater. The coir dust contains lignocellulosic fibers, including cellulose, hemicellulose, and lignin, which provide numerous functional groups like hydroxyl, carboxyl, and methoxy, allowing strong interaction with dye molecules (12,13).Numerous studies have shown that coconut coir dust is an effective adsorbent for CV removal, with significant dye uptake observed in both raw and chemically modified forms. The adsorption capacity of coconut coir dust is primarily attributed to its high surface area, porosity, and functional group composition (14,15). Chemical modifications such as acid or alkali treatments enhance the adsorption efficiency by increasing the number of active sites available for dye binding (16,17).The adsorption process of CV onto coconut coir dust is governed by various mechanisms, including electrostatic interaction, hydrogen bonding, and physical adsorption (18). The dye molecules, being positively charged, interact with the negatively charged surface of coconut coir fibers, leading to effective removal from aqueous solutions (19). The process is highly dependent on factors such as pH, temperature, initial dye concentration, and contact time, with optimum conditions varying depending on the specific type of coir dust and its modification (20,21).Coconut coir dust is not only an efficient adsorbent for CV dye removal but also a renewable and inexpensive material, offering an environmentally friendly solution for wastewater treatment. Its low cost and wide availability make it an attractive alternative to conventional adsorbents, especially in regions where coconuts are abundantly produced (22,23). Furthermore, studies have indicated that the adsorption process follows well-established models such as Langmuir and Freundlich isotherms, indicating monolayer and multilayer adsorption, respectively, on the surface of the coir dust (24,25).In conclusion, coconut coir dust presents an effective and sustainable adsorbent for Crystal Violet dye removal from wastewater, offering both environmental and economic benefits while addressing the growing issue of wastewater contamination (26).

2.3. Banana peels as an Adsorbent for Crystal Violet Removal

Banana peels are rich in cellulose, hemicellulose, lignin, and particularly pectin—components that contribute functional groups such as hydroxyl, carboxyl, and amino groups, enhancing their adsorption properties. Similarly, orange peels contain substantial amounts of cellulose, pectin, and essential oils, offering multiple binding sites for dye molecules. Annadurai et al. (2002) conducted pioneering research demonstrating the efficiency of banana and orange peels in removing Crystal Violet (CV), a cationic dye, from wastewater. Their work highlighted the vital role of pectin and cellulose in facilitating dye adsorption through electrostatic interactions and hydrogen bonding mechanisms [27]. Later studies confirmed these findings. For instance, Hameed (2009) studied the use of agricultural waste materials, including banana peels, and reported high adsorption capacities for basic dyes such as CV due to the presence of polar functional groups [28]. Similarly, Nguyen et al. (2013) demonstrated that orange peel-derived adsorbents effectively removed CV under varying conditions of pH and contact time, attributing the removal efficiency to the surface chemistry rich in carboxylic and phenolic groups [29].The preparation methods such as washing, drying, grinding, and sometimes chemical activation (e.g., acid or base treatment) significantly influence the adsorption capacity of these peels. Modified peels, particularly those treated with acids or alkalis, exhibit enhanced adsorption capabilities by increasing surface area and exposing more functional groups for dye binding [30].The advantages of using banana and

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orange peels include their low cost, high efficiency, sustainability, and the possibility of regeneration and reuse. However, scalability and disposal of spent adsorbents remain challenges that require further research.

2.4 Bamboo Sawdust as an Adsorbent for Crystal Violet Removal:

Limited studies investigated bamboo sawdust for removing Crystal Violet (CV) dye from wastewater. One study used sodium carbonate-modified *Bambusa tulda* sawdust, which showed improved adsorption due to functional groups like hydroxyl and carboxyl (32). The process followed Langmuir isotherm and pseudo-second-order kinetics, with optimal removal at neutral pH and equilibrium reached within 60 minutes (32).While direct work on sawdust was sparse, bamboo charcoal combined with ZnO nanoparticles showed effective dye removal via both adsorption and photocatalytic degradation (33).Additionally, research on other lignocellulosic wastes demonstrated similar adsorption mechanisms, supporting bamboo sawdust's potential as a sustainable adsorbent (34).

2.5 Neem Leaves as an Adsorbent for Crystal Violet Removal:

Neem leaves (*Azadirachta indica*), rich in cellulose, lignin, and bioactive compounds, have been investigated as a low-cost and eco-friendly adsorbent for the removal of Crystal Violet (CV) dye from wastewater (35). Their surface functional groups such as hydroxyl and carboxyl facilitate electrostatic attraction, hydrogen bonding, and π-π interactions with dye molecules (36).Chemically modified Neem leaf adsorbents, particularly those activated with phosphoric acid or zinc chloride, have shown enhanced adsorption capacities (37).Adsorption of CV typically follows pseudo-second-order kinetics and fits well with the Langmuir isotherm model, indicating chemisorption and monolayer adsorption (38).Optimal removal occurs under alkaline pH conditions, with rapid equilibrium generally achieved within 60–120 minutes (39).Although Neem leaf-based adsorbents exhibit good initial performance, studies limited information on their regeneration, although some desorption methods show promise for reusability (40).

Table 1. Factors Influencing Adsorption

Adsorbent	**pH**	**Initial Dye Concentration**	**Contact Time**	**Temperature**	**Surface Modification**
Rice Husk	Optimal at **alkaline**	Higher concentration → increased adsorption (up to saturation)	Rapid initial, equilibrium in ~60–120 min	Higher temp may enhance adsorption	Acid/base treatment increases porosity and active sites
Coconut Coir Dust	Optimal at **alkaline/neutral**	Influences adsorption capacity; high concentrations may need modified coir	Typically **<2 hours** for equilibrium	Elevated temp improves uptake	Acid/alkali activation improves surface area
Banana Peel	Better at **moderate to alkaline**	Higher concentration increases rate initially	Equilibrium reached in **~60–120 min**	Slight temp increase beneficial	Acid/base treatments expose functional groups
Orange Peel	Best at **alkaline**	Affects saturation and kinetics	Usually **<2 hours**	Mildly elevated temperatures improve adsorption	Chemical activation enhances surface functionality
Bamboo Sawdust	Optimal at **alkaline**	Directly affects adsorptive performance	Rapid uptake, equilibrium within **~2 hours**	Higher temp increases efficiency	Acid/base treatments improve adsorption sites
Neem Leaves	Optimal at **alkaline**	Strongly affects initial uptake and capacity	Equilibrium in **60–120 min**	Adsorption favored at higher temperatures	Phosphoric acid/$ZnCl_2$ treatment improves adsorption

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Table 2. Adsorption mechanism

Adsorbent	Main Functional Groups	Adsorption Mechanisms	Nature of Interaction
Rice Husk	Hydroxyl, carboxyl, silanol (Si–OH), phenolic	**Electrostatic attraction**, **hydrogen bonding**, **π–π interactions**	Combination of **physisorption** and **chemisorption**
Coconut Coir Dust	Hydroxyl, carboxyl, methoxy	**Electrostatic interaction**, **hydrogen bonding**, **physical adsorption**	Primarily **physisorption**, some **chemisorption**
Banana Peel	Hydroxyl, carboxyl, amino	**Electrostatic interaction**, **hydrogen bonding**	Mostly **physisorption** with some **chemisorption**
Orange Peel	Carboxylic, phenolic, hydroxyl	**Electrostatic interaction**, **hydrogen bonding**	**Physisorption-dominant**
Bamboo Sawdust	Hydroxyl, carboxyl	**Electrostatic attraction**, **π–π stacking**, **hydrogen bonding**	Mixed **chemisorption and physisorption**
Neem Leaves	Hydroxyl, carboxyl, aromatic bioactives	**Electrostatic interaction**, **π–π interactions**, **hydrogen bonding**	Strong **chemisorption**, monolayer adsorption

Table 3. Adsorption Isotherms and Kinetics

Adsorbent	Isotherm Models	Kinetic Models	Interpretation
Rice Husk	**Langmuir**, Freundlich	**Pseudo-second-order**	Suggests **monolayer adsorption** on homogeneous sites and **chemisorption**
Coconut Coir Dust	**Langmuir**, Freundlich	**Pseudo-second-order**	Indicates both **monolayer and multilayer** adsorption; **chemical interactions** dominate
Banana Peel	Freundlich (often better fit), Langmuir	**Pseudo-second-order**, sometimes pseudo-first-order	Multilayer adsorption on heterogeneous surface; **diffusion-controlled** and **chemisorption**
Orange Peel	**Langmuir**, Freundlich	**Pseudo-second-order**	Suggests **monolayer adsorption**; kinetic data implies **chemisorption**
Bamboo Sawdust	**Langmuir**, Freundlich	**Pseudo-second-order**	Favors **monolayer adsorption**; **high correlation** with chemisorption mechanisms
Neem Leaves	**Langmuir** (best fit), Freundlich	**Pseudo-second-order**	Strong **chemisorption**, indicative of **monolayer formation**

3. REGENERATION AND REUSABILITY

- Most biosorbents can undergo **1–3 regeneration cycles** with acceptable efficiency using acid, base, or solvent-based desorption.
- **Chemical stability and structural integrity** are key challenges for plant-based adsorbents during reuse.
- There is a need for **standardized regeneration protocols** and **life-cycle analyses** to fully assess sustainability.

So we can say that, while plant-based adsorbents offer eco-friendly and cost-effective solutions for dye removal, **regeneration and reusability remain under-researched areas**, especially for large-scale applications. Future studies should focus on enhancing **mechanical stability and regeneration efficiency** to improve practicality.

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4. CONCLUSION

Plant-derived bio sorbents have emerged as sustainable, low-cost, and efficient alternatives to conventional materials for the removal of Crystal Violet dye from wastewater. Derived from abundant agricultural by-products such as rice husk, coconut coir dust, banana and orange peels, bamboo sawdust, and neem leaves, these bio-based materials are rich in functional groups that facilitate effective dye adsorption through mechanisms like electrostatic interactions, hydrogen bonding, and π–π stacking. Their use not only enhances dye removal efficiency but also contributes to agricultural waste repurposing, supporting the principles of green chemistry and the circular economy. Due to their biodegradability, local availability, and environmental compatibility, these adsorbents are well-suited for large-scale wastewater treatment applications. However, practical limitations such as limited regeneration capacity, reduced efficiency upon reuse, and scalability issues remain significant challenges. To fully realize their potential in industrial applications, future research should focus on improving surface modification techniques, deepening the understanding of adsorption mechanisms, and developing cost-effective regeneration strategies that enhance reusability and operational feasibility.

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