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Agricultural Waste–Derived Activated Carbons for Methylene Blue Adsorption: A Comprehensive Review

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Abstract:
The discharge of synthetic dyes into aquatic ecosystems represents a persistent environmental challenge due to their toxicity, complex chemical structure, and resistance to biodegradation. Among these dyes, methylene blue (MB), a cationic thiazine dye, is widely used in textile and clinical industries and poses significant ecological and human health risks when inadequately treated. Activated carbon derived from agricultural waste biomass has emerged as an efficient, low-cost, and sustainable adsorbent for MB removal owing to its high surface area, well-developed porosity, surface functionality, and valorisation of abundant biowastes. This review critically evaluates recent advancements in MB adsorption using activated carbons derived from cashew nut shell, rice husk, pea shells, date stones, fox nutshell, banana stem, water hyacinth, and other lignocellulosic residues, as well as graphene-based carbons. The review provides a systematic comparison of precursor processing, chemical and physical activation strategies ($ZnCl_2$, H_3PO_4, KOH), adsorption behavior under varying pH, dose, and contact time, and mechanistic interpretations using Langmuir and Freundlich isotherms, pseudo-second-order kinetics, and intraparticle diffusion descriptors. Regeneration and reusability strategies are analyzed to assess industrial applicability and lifecycle sustainability. Adsorption capacities from selected agricultural wastes are compared, showing high performance up to 968.74 mg g-1 for fox nutshell activated carbon and >160 mg g-1 for date-stone carbon, demonstrating strong competitive potential against commercial carbons. Environmental and economic implications of converting global biomass waste streams into engineered adsorbents are critically assessed. Finally, technical gaps are identified regarding scale-up, regeneration efficiency, multi-pollutant systems, and long-term stability. The insights provided herein are expected to guide future optimization toward circular-economy-aligned wastewater treatment technologies using agricultural waste derived activated carbons.

Keywords: Methylene blue; Agricultural waste; Activated carbon; Adsorption; Isotherms; Kinetics; Regeneration.

Highlights

- Agricultural waste valorization yields sustainable activated carbons with high MB uptake.
- Chemical activation ($ZnCl_2$, H_3PO_4, KOH) improves surface area, porosity, and functional sites.
- Adsorption typically follows Langmuir isotherm and pseudo-second-order kinetics.
- Some biomasses (fox nutshell, pea shell) exceed 200–900 mg g-1 adsorption capacity.
- Regeneration efficiency and economic scalability remain key research priorities.

1. Introduction

Synthetic dyes are major pollutants found in wastewater effluents from textile, leather, pulp, pharmaceutical, and food industries. Their complex aromatic structures impart high stability, making them resistant to biodegradation and conventional treatment. Methylene blue (MB), a model cationic dye, is widely reported due to its high aqueous solubility, intense chromophore, and toxicity concerns

[1]. Water contaminated with dyes hinders light penetration, impacts aquatic photosynthesis, and introduces mutagenic and carcinogenic threats to organisms [1,2]. With increasing regulatory pressure on industrial discharge, efficient dye remediation strategies are essential. Activated carbon (AC) is well-recognized as an effective adsorbent for diverse pollutants because of its high surface area, tunable pore distribution, and rich surface chemistry [3,4]. However, commercial AC production from coal or petroleum precursors is expensive and environmentally taxing. Researchers have thus turned to sustainable feedstocks: agricultural biowastes such as fox nutshell [3], date stones [4], cashew nut shell [5], pea shell [6], water hyacinth [7, 8], banana stem [9], Ficus carica bast [10], rice husk [11] and peach stones [12]. These wastes are abundantly available, low-cost, and generate carbon-rich precursors with heteroatoms (O, N, S) beneficial to adsorption properties. Chemical treatment (KOH, $ZnCl_2$, H_3PO_4) enables tailored pore architectures and oxygenated surface groups capable of electrostatic interaction, π–π bonding, and hydrogen bonding with MB molecules [13].

Several studies have demonstrated outstanding adsorption capacities, from moderate performance (~75 mg g^{-1}) for rice husk [11] and water hyacinth [7] to remarkably high values approaching ~969 mg $g^{-1}$for fox-nutshell-derived AC [3]. Despite impressive lab-scale results, challenges remain in regeneration efficiency, sorbent stability, and industrial deployment under real wastewater matrices. This review consolidates technological advancements in agricultural waste–derived activated carbons for MB removal, emphasizing adsorption mechanisms, environmental sustainability, and future commercial translation.

2. Dye Pollution Concerns and Wastewater Treatment

The synthetic dyes represent a major class of aquatic contaminants owing to their high chromophoric intensity, complex aromatic molecular structures, and pronounced resistance to biodegradation. Industrial wastewater originating from textile, leather, pulp and paper, pharmaceutical, and cosmetic sectors is often laden with a heterogeneous mixture of dissolved and suspended solids, surfactants, alkali salts, chlorinated intermediates, and persistent organic pollutants that inhibit the efficiency of conventional physicochemical and biological treatment processes. Dyes, particularly methylene blue (MB), exhibit strong visible-light absorption and can impart coloration to water bodies even at ultra-low concentrations. Notably, MB levels as low as 1 mg L^{-1} impart a distinct blue tint to water, compromising its aesthetic quality and rendering it unsuitable for potable use or aquatic ecological balance [7]. Moreover, MB and similar cationic dyes can reduce dissolved oxygen levels, inhibit photosynthetic activity by blocking light penetration, and form toxic transformation products under environmental redox conditions. Their persistence and bioaccumulation potential further raise concerns regarding cytotoxic, mutagenic, and neurotoxic effects in exposed organisms, including humans.

These challenges necessitate the development of advanced and sustainable remediation approaches capable of effectively removing dye molecules from industrial effluents while minimizing secondary pollution. Activated carbon adsorption, particularly from renewable biomass sources, has therefore become one of the most promising strategies for environmental dye mitigation.

2.1 Environmental Impacts of Methylene Blue

The methylene blue (MB) is extensively utilized across a wide spectrum of industrial and biomedical sectors, including textile dyeing, paper printing, leather finishing, cosmetic formulations, and clinical diagnostics, particularly as a biological stain and redox indicator. However, its continuous discharge into aquatic ecosystems poses significant environmental and health challenges. Upon entering natural water bodies, MB strongly absorbs visible light, thereby reducing sunlight penetration and adversely affecting photosynthetic processes essential for sustaining aquatic flora and overall ecosystem productivity [1]. Additionally, MB can undergo oxidative and photochemical transformations, generating potentially hazardous intermediate products that may exhibit increased toxicity compared to the parent compound. Due to its cationic and aromatic nature, MB readily adsorbs onto suspended solids and sediments, facilitating bioaccumulation and subsequent trophic transfer in aquatic food webs. Exposure to elevated

concentrations of MB is known to cause detrimental physiological responses in humans and animals, such as dermal irritation, gastrointestinal distress, methemoglobinemia, hemolytic anemia, and respiratory complications [2,4]. These documented ecological and toxicological risks underline the urgent necessity for efficient MB removal from industrial effluents, establishing it not only as a regulatory obligation but also as a critical component of environmental protection and public health preservation.

2.2 Challenges in Conventional Treatment

A variety of wastewater treatment strategies have been employed to address dye-laden industrial effluents; however, each conventional method possesses inherent limitations that hinder efficient and sustainable removal. Chemical coagulation and flocculation techniques, while effective in destabilizing chromophoric compounds, typically result in the generation of secondary sludge that necessitates further disposal. Advanced oxidation processes such as Fenton, ozonation, and photocatalysis are capable of degrading complex dye molecules but often require expensive reagents and may achieve only partial mineralization, leaving behind toxic transformation products. Membrane-based separation offers high purification capability, yet membrane fouling and substantial operational energy demands restrict its scalability for continuous industrial treatment. Electrochemical approaches provide strong oxidative potential but require sophisticated instrumentation and maintenance. Even when reported dye removal efficiencies exceed 90%, the persistence of hazardous aromatic intermediates remains a serious concern, underscoring the limitations of current technologies in achieving complete remediation [2]. In contrast, adsorption-based treatment has emerged as one of the most promising alternatives owing to its operational simplicity, cost-effectiveness, adaptability to diverse effluent compositions, reusability of adsorbents, and consistently high dye removal performance [3,7]. Consequently, adsorption, particularly using renewable and environmentally benign activated carbons, continues to gain prominence in sustainable wastewater purification strategies. The common wastewater treatment strategies given in the

Table 1: Common wastewater treatment strategies

Technique	**Limitations**
Chemical coagulation/flocculation	Generates secondary sludge
Advanced oxidation processes	High reagent cost, partial mineralization
Membrane filtration	Fouling, high operational energy
Electrochemical methods	Complex instrumentation

2.3 Adsorption Advantage for Dye Removal

Adsorption has emerged as one of the most efficient and versatile strategies for dye remediation due to its ability to remove contaminants even at ultra-low concentrations while maintaining operational simplicity and cost-effectiveness. Activated carbon, in particular, is widely recognized for its exceptionally high surface area, tunable pore architecture, and rich surface chemistry, which collectively facilitate rapid mass transfer and high adsorption capacities for a broad range of dye molecules. Its fast adsorption kinetics allow efficient pollutant capture within short contact times, and its compatibility with both batch and continuous reactor configurations makes it suitable for large-scale industrial applications. Moreover, activated carbon demonstrates robust applicability in complex wastewater systems containing multiple organic and inorganic constituents, where other treatment processes may fail due to competitive reactions or matrix interference. Importantly, the development of activated carbons derived from agricultural waste materials introduces an additional dimension of sustainability: not only do these bio-

adsorbents effectively treat dye-polluted effluents, but they also valorize abundant biomass residues that would otherwise contribute to environmental burdens. By integrating waste-to-resource principles with advanced pollutant removal, agricultural waste–based activated carbons strongly align with circular economy models and global net-zero emission objectives, positioning them as a pivotal solution for future eco-friendly wastewater treatment infrastructure.

3. Activated Carbon and Adsorbent Technologies

The activated carbon consists of aromatic, microcrystalline structures with micropores (<2 nm), mesopores (2–50 nm), and functional groups conducive to pollutant capture. Performance is driven by surface chemistry and porosity.

3.1 Agricultural Biomass as Carbon Precursors

The agricultural waste materials are primarily composed of cellulose (40–50%), hemicellulose (15–30%), and lignin (15–30%), which together provide a carbon-rich matrix suitable for conversion into activated carbon precursors. When subjected to pyrolysis and appropriate chemical activation processes, these lignocellulosic components degrade into highly porous carbon structures with functional surface groups favourable for pollutant adsorption. In the reviewed studies, diverse agricultural by-products such as cashew nut shell, rice husk, pea shell, fox nutshell, banana stem, water hyacinth, pine sawdust, and date stones have been successfully utilized as renewable and economically viable precursors for activated carbon production.

3.2 Activation Strategies

The activation plays a crucial role in transforming raw lignocellulosic biomass into adsorbents with highly developed porosity and enriched surface functionalities. During the activation process, the organic matrix undergoes thermal decomposition and chemical etching, which effectively removes volatile components and creates an extensive pore network essential for enhanced adsorption performance. Different activating agents influence the pore structure development and chemical characteristics of activated carbon depending on their reactivity with the char structure. The KOH activation is known for promoting the formation of micropores through strong redox interactions between alkali metals and carbon frameworks, yielding high internal surface areas suitable for monolayer adsorption of small dye molecules [6]. On the other hand, H_3PO_4 activation enhances mesoporosity and introduces acidic surface oxygenated groups capable of improving cationic dye binding through electrostatic attraction and hydrogen bonding [7,9]. Additionally, $ZnCl_2$ activation inhibits tar formation during pyrolysis and facilitates cross-linking reactions, which increase carbon yield while producing a balanced micro- and mesoporous structure. Notably, fox-nutshell-derived activated carbon activated by $ZnCl_2$ demonstrated a superior BET surface area of 2869 $m^2\ g^{-1}$, among the highest reported for biomass-based adsorbents used in methylene blue removal [11]. These findings confirm that the choice of chemical activator plays a decisive role in tailoring the adsorption efficiency and physicochemical behavior of agricultural waste-derived activated carbons. The role of common chemical activators in biomass-based activated carbon production are given in Table 2.

Table 2: Role of common chemical activators in biomass-based activated carbon production

Activator	Primary Function During Activation	Ref.
KOH	Enhances microporosity by strong etching and formation of internal channels	[6]
H_3PO_4	Increases mesoporosity and introduces acidic surface functional groups (–OH, –COOH) favourable for dye adsorption	[7,9]

$ZnCl_2$	Suppresses tar formation, improves carbon yield, produces hierarchical pore structures; highest BET surface area achieved (fox nutshell AC: 2869 $m^2 g^{-1}$)	[3]

3.3 Mechanisms of Adsorption Enhancement

The agricultural waste–derived activated carbons exhibit superior adsorption performance due to their unique structural and chemical characteristics imparted by lignocellulosic precursors. The presence of oxygenated functional groups and partially graphitized aromatic domains facilitates strong π–π stacking interactions between the conjugated structure of methylene blue (MB) molecules and the carbon basal planes, while electrostatic attraction between negatively charged surface sites and MB^+ cations further enhance adsorption affinity. In addition, the inherently hierarchical pore structure originating from lignin–cellulose decomposition promotes rapid intraparticle diffusion, enabling efficient penetration of dye molecules into both micro- and mesoporous networks. Residual heteroatoms such as nitrogen, oxygen, and sulfur, introduced during thermal degradation of biomass, contribute additional active binding sites that enhance chemical interaction through hydrogen bonding and donor–acceptor mechanisms. Collectively, these physicochemical advantages allow agricultural waste–derived activated carbons to achieve adsorption efficiencies that can surpass those of traditional coal-based activated carbons while simultaneously offering significant economic and environmental benefits, thereby supporting their adoption as sustainable materials in advanced wastewater treatment technologies.

4. Review of Agricultural Waste–Derived Activated Carbons for MB Adsorption

A detailed and critical evaluation of adsorption performance enables a systematic understanding of how agricultural waste–derived activated carbons function as highly efficient sorbents for methylene blue removal. This review organizes the discussion around several key scientific criteria that govern adsorption behavior. First, precursor type influences the inherent carbon content, ash composition, and heteroatom distribution in the raw biomass. Second, activation methods determine the degree of porosity development and surface functionalization, which directly impact adsorption capacity. Third, adsorption conditions such as solution pH, initial dye concentration, temperature, and contact time dictate the sorption driving forces and equilibrium attainment. Furthermore, isotherm modeling provides insights into surface homogeneity and adsorption mechanisms, distinguishing between monolayer and multilayer coverage. Kinetic and diffusion analyses clarify whether the rate-controlling step involves chemisorption, film diffusion, or intraparticle transport limitations. Thermodynamic parameters reveal the spontaneity, heat flow nature, and energetics of the adsorption process, enhancing the mechanistic interpretation. Lastly, the regeneration efficiency assesses the practical feasibility of multiple adsorption–desorption cycles, ensuring sustainability and cost-effectiveness in real wastewater treatment scenarios. Together, these categories form a comprehensive scientific framework for assessing and comparing the performance of biomass-derived activated carbons.

4.1 Precursor Classification: Agricultural Waste Sources

The agricultural precursors examined in the reviewed studies encompass a wide range of lignocellulosic materials including nut shells such as cashew nut shell [5], pea shell [6], and fox nutshell [3], crop residues like rice husk [11] and banana stem [9], aquatic biomass including water hyacinth [7], wood-derived waste such as pine sawdust [1], and fruit seeds like date stones [4]. These biomass feedstocks possess high fixed carbon content, low ash concentration, and structurally complex lignocellulosic matrices that facilitate the formation of well-developed porous carbon networks upon pyrolysis and chemical activation.

Table 3: BET surface area and textural properties of agricultural waste–derived activated carbons used for MB adsorption

Adsorbent Source	**Activation**	**BET Surface Area ($m^2 g^{-1}$)**	**Major Pore Type**	**Reference**
Cashew nut shell	$ZnCl_2$	1050	Micropores	[5]
Rice husk	H_3PO_4	350–500	Mesopores	[11]
Pea shell	KOH	1122	Micropores	[6]
Fox nutshell	$ZnCl_2$	2869	Ultra-micropores	[3]
Pine sawdust	Natural	150–200	Mixed	[1]
Banana stem	H_3PO_4	600–900	Mesopores	[9]
Water hyacinth	H_3PO_4	450–600	Micro-mesopores	[7]
Date stones	NaOH	720	Micropores	[4]

The fox nutshell clearly yields extraordinary performance due to its exceptionally high surface area and micropore volume, which greatly enhance its adsorption affinity toward MB molecules [3]. The presence of inherent heteroatoms and aromatic structures further contributes to the development of functionalized activated carbons, leading to increased surface reactivity and dye-binding efficiency. Given their vast availability, renewable origin, and cost-effectiveness, these agricultural wastes represent highly promising and sustainable precursors for engineered activated carbons targeting methylene blue removal from wastewater systems. The agriculture waste precursor, activation chemicals and specific surface area are given in table 3 and Maximum adsorption capacities (q_{max}) of various agricultural waste activated carbons are shown in Table 4.

Table 4. Maximum adsorption capacities (q_{max}) of various agricultural waste activated carbons

Adsorbent	**Adsorption Capacity q_{max} ($mg\ g^{-1}$)**	**Best-Fit Isotherm**	**Reference**
Fox nutshell AC	968.7	Langmuir	[3]
Pea shell AC	219.6	Langmuir	[6]
Date stones AC	163.7	Freundlich	[4]
Pine sawdust	142	Langmuir	[1]
Water hyacinth AC	98.6% removal	—	[7]

Cashew nut shell	249.9	PSO–L & Freundlich	[5]

4.2 Activation Method Effects

The chemical activation plays a crucial role in enhancing the adsorption performance of biomass-derived activated carbons by significantly increasing their porosity and functional group density compared to physical activation alone. Among the commonly used activating agents, $ZnCl_2$ effectively dehydrates lignocellulosic biomass, suppressing tar formation during carbonization and promoting the development of an extensive ultra-microporous network, which enhances dye access to active sites. This method has yielded some of the highest reported textural properties, including a remarkable BET surface area of 2869 $m^2\ g^{-1}$ for fox nutshell–derived activated carbon [3]. Similarly, H_3PO_4 activation introduces acidic oxygen-containing functionalities such as –OH and –COOH groups on the carbon surface, improving electrostatic attractions toward cationic dyes like MB^+ while generating mesoporous channels that facilitate rapid intraparticle diffusion [7, 9]. In contrast, KOH activation operates through a strong etching mechanism that widens existing pores and develops interconnected micro- and mesopore pathways, enhancing both mass transfer and π-electron interactions between the carbon surface and the aromatic dye molecules, ultimately favouring chemisorption [6]. Collectively, these chemical activation strategies lead to substantial increases in surface area, active binding sites, and diffusion pathways, resulting in markedly improved adsorption capacities and overall removal efficiency of methylene blue from contaminated water systems.

4.3 Adsorption Operating Conditions

The adsorption performance of agricultural waste–derived activated carbon toward methylene blue (MB) is highly sensitive to operating parameters that influence both surface chemistry and mass transfer behavior. Solution pH plays a critical role, because at higher pH values the activated carbon surface becomes increasingly negatively charged, enhancing the electrostatic attraction toward cationic MB^+ molecules and improving removal efficiency [1,9]. Contact time affects the progression of adsorption from rapid initial uptake — driven by the abundance of available active sites — to a slower intraparticle diffusion–controlled stage as equilibrium approaches [2]. The adsorbent dose directly influences removal efficiency; increasing mass provides more active binding sites, although the equilibrium adsorption capacity per unit mass (q_e) typically decreases due to site aggregation and overlapping diffusion zones [7]. Meanwhile, initial MB concentration determines the driving force for MB diffusion into pores and adsorption onto functional groups; higher concentrations promote monolayer saturation and can reveal the maximum adsorption capacity (q_{max}) governed by Langmuir behaviour [3]. Across the reviewed studies, equilibrium is generally achieved within 60–120 minutes, demonstrating the rapid adsorption kinetics of these biomass-derived materials. For example, banana-stem activated carbon achieved >99% MB removal within 90 minutes at pH 11 [9], while fox-nutshell activated carbon exhibited a dramatic increase in q_e from 249 to 968 mg g^{-1} with increasing MB concentration, highlighting exceptional adsorptive potential [3]. The key parameters which influence the adsorption of MB are given in the table 5.

Table 5: Influence of parameters on MB adsorption

Parameter	**Influence on MB Adsorption**	**Ref.**
pH	Higher pH increases negative surface charge, improving MB^+ electrostatic binding	[1,9]

Contact time	Rapid initial adsorption followed by slower diffusion-controlled uptake	[2]
Adsorbent dose	Removal efficiency increases but q_e decreases due to site saturation effects	[7]
Initial MB concentration	Elevated concentration enhances monolayer formation at active sites	[3]

4.4 Isotherm Behavior & Adsorption Mechanism

Most studies confirm monolayer chemisorption via Langmuir model:

$$\frac{1}{q_e} = \frac{1}{q_{max}} + \left(\frac{1}{q_{max}.K_L}\right) + \frac{1}{Ce}$$

where,

K_L=Langmuir constant (dm^{-3} mol^{-1})

q_{max} =Monolayer langmuir adsorption ($mg\ g^{-1}$)

Table 6: Adsorbent and isotherm

Adsorbent	**Isotherm**	**Mechanism**	**Ref**
Fox nutshell AC	Langmuir	Monolayer coverage	[3]
Pea shell AC	Langmuir	Cation-π interaction	[6]
Pine sawdust	Langmuir	Electrostatic + chemisorption	[1]
Water hyacinth	Langmuir & Freundlich co-fit	Heterogeneous surface	[7]

Langmuir dominance indicates uniform, high-energy binding site distribution.

4.5 Kinetic Modeling and Rate-Limiting Steps

The kinetic modeling results reported across the reviewed studies consistently indicate that the pseudo-second-order (PSO) model provides the best fit for methylene blue adsorption onto agricultural waste–derived activated carbons, confirming that chemisorption is the dominant rate-controlling mechanism [1-3, 5-7]. Complementary Weber–Morris intraparticle diffusion analyses further reveal a multi-stage adsorption behavior, wherein an initial rapid uptake occurs due to abundant available active sites at the external surface, followed by a slower phase governed by intraparticle diffusion as dye molecules migrate into the interior pore network. This combined observation illustrates that adsorption proceeds through external mass transfer in the early stage and becomes increasingly influenced by diffusion resistance within micropores and mesoporous structures during later progression toward equilibrium. The almost all studies show pseudo-second-order (PSO) is superior:

$$\frac{t}{q_t} = \frac{1}{ks.qe^2} + \frac{t}{q_e}$$

where,

q_t (mg g^{-1}) =amount of adsorbate adsorbed at time t

q_e (mg g^{-1})=amount of adsorbate adsorbed at eq.

k_s (g mg^{-1} min^{-1}) =Pseudo second order rate constant

4.6 Thermodynamic Parameters

Thermodynamic analyses reveal that the adsorption behavior of methylene blue onto agricultural waste–derived activated carbons can vary depending on the precursor material and resulting surface chemistry. For example, fox-nutshell-based activated carbon exhibits a negative enthalpy change ($\Delta H° = -2.93$ kJ mol^{-1}), indicating an exothermic process in which adsorption becomes less favorable at elevated temperatures. In contrast, activated carbon produced from pine sawdust demonstrates endothermic adsorption behavior, where dye uptake increases with temperature due to enhanced dye diffusion and activation of newly accessible adsorption sites. Overall, the thermodynamic trends suggest that both physisorption and chemisorption mechanisms contribute to methylene blue removal, with the specific heat effects influenced by a combination of pore structure, surface functionality, and the presence of active heteroatom groups on the carbon surface.

4.7 Regeneration & Reusability

The regeneration of spent adsorbents is a crucial requirement for commercial implementation of adsorption-based dye removal technologies, as it determines both economic practicality and environmental sustainability. Different regeneration strategies have been employed for agricultural waste–derived activated carbons with varying degrees of success. Solvent washing has demonstrated good performance in recovering adsorption capacity where dye uptake is largely governed by physical interactions, allowing desorption with minimal structural damage to the carbon matrix [6]. Thermal regeneration is also widely used; however, repeated high-temperature treatments can cause pore collapse, surface oxidation, and gradual loss of active sites, thereby reducing the long-term efficiency of the adsorbent. More advanced approaches such as photocatalytic regeneration, particularly when using reduced graphene oxide (rGO)–based composites, have shown excellent potential by achieving up to 98% adsorption capacity retention after five reuse cycles through simultaneous dye degradation and surface restoration [14]. These hybrid adsorbents enable adsorption–photodegradation synergy, reducing secondary waste generation and enhancing recyclability. Overall, regeneration performance must be evaluated not only in terms of percentage capacity retained across multiple cycles, but also by considering cost, energy consumption, and the environmental impact of the regeneration method, which together govern the practical deployment of activated carbon in sustainable wastewater treatment systems. The regeneration is critical for industrial application.

5. Economic and Environmental Sustainability

Agricultural waste-derived activated carbons present a dual advantage:

i. **Waste Valorization**

The large quantities of lignocellulosic by-products such as shells, husks, stems, and sawdust are generated annually and are frequently disposed of through landfilling or open-air burning, contributing to significant environmental pollution and waste accumulation challenges. Valorizing these residues by converting them into high-value activated carbon reduces landfill burden, mitigates particulate emissions associated with biomass burning, and lowers overall waste management costs, thereby supporting sustainable resource utilization within circular economy frameworks.

ii. **Cost Efficiency**

The biowastes based activated carbon offers substantial sustainability advantages as compared with commercial activated carbon produced from coal or petroleum-derived coke. It significantly lowers raw

material costs, minimizes the overall carbon footprint associated with production, and reduces dependence on non-renewable fossil-based precursors, making it a more environmentally responsible alternative for large-scale adsorption applications.

iii. **Energy and Chemical Inputs**

The overall sustainability of biomass-derived activated carbon production is influenced by several key processing factors, including the pyrolysis temperature, which affects carbon yield and energy consumption; the choice of chemical activating agents, where materials such as $ZnCl_2$ require careful recovery and disposal due to environmental hazards, while H_3PO_4 offers a comparatively more eco-friendly activation pathway; and the energy requirements for adsorbent regeneration**,** which determine the long-term environmental and economic viability of repeated adsorption–desorption cycles.

iv. **Water Treatment Sustainability Index**

The performance of biomass-derived activated carbons must be evaluated not only on their initial removal efficiency but also on regeneration success rate, adsorption capacity retention over multiple cycles, and the absence of toxic leachates released during operation. When these sustainability factors are considered alongside economic metrics, optimally activated low-cost agricultural waste–based carbons have been shown to outperform commercial activated carbons in terms of adsorption efficiency per unit cost, further strengthening their potential for large-scale industrial wastewater treatment applications.

6. Research Gaps and Future Scope

In spite of the demonstrated potential of agricultural waste–derived activated carbons for methylene blue remediation, several barriers must be addressed before large-scale adoption can be realized. A major limitation in current research is the scarcity of real-wastewater studies, as most experiments rely on synthetic dye solutions that overlook competitive adsorption phenomena arising from complex matrices containing surfactants, salts, and co-pollutants. This necessitates the development of mixed-pollutant and competitive adsorption models to better simulate industrial effluent conditions. Additionally, although many studies report high adsorption efficiency, regeneration durability is commonly validated for only three to five cycles, leaving long-term performance largely unknown; future work must therefore target >10 multi-cycle validation to ensure industrial robustness. Another constraint is the overreliance on batch-mode experiments**,** which lack scalability; transitioning toward continuous flow and fixed-bed column designs is essential for real treatment applications. Mechanistic understanding also remains incomplete due to poorly defined surface chemistry, highlighting the need for advanced surface characterization techniques such as XPS and FTIR mapping to elucidate bonding interactions. Furthermore, the sustainability of chemical activation remains under scrutiny, particularly with respect to $ZnCl_2$ disposal and acid consumption, encouraging the exploration of green activation routes and self-activation approaches. Finally, techno-economic assessments and life-cycle analyses are rarely conducted, yet are critical for evaluating commercial feasibility, carbon footprint impacts, and alignment with circular-economy principles. In this context, integration of adsorption with photocatalytic regeneration, especially using carbon-based composites, has emerged as a highly promising strategy to achieve continuous and sustainable dye degradation [14].

7. Conclusion:

The agricultural waste-derived activated carbons have proven to be highly efficient, sustainable, and cost-effective adsorbents for methylene blue removal. The reviewed literature demonstrates that surface area, pore distribution, and the presence of functional groups strongly depend on precursor selection and chemical activation methodology. Adsorption behaviors commonly exhibit Langmuir monolayer models and pseudo-second-order kinetics, confirming the central role of chemisorption mechanisms. Exceptionally high adsorption capacities have been achieved with certain biomass precursors including fox nutshell (up to 968.7 mg g^{-1}), highlighting strong potential to surpass traditional commercial activated carbons. Thermodynamic analyses suggest both physical and chemical binding mechanisms

influence performance depending on pore characteristics and solution chemistry. However, challenges remain in regeneration stability, scale-up feasibility, and performance in real-world wastewater containing competing contaminants. Future innovations should focus on hybrid materials, green activation processes, multi-cycle reusability, and integration with photocatalytic degradation pathways. Overall, agricultural waste valorization into activated carbon represents a promising circular-economy approach to mitigate dye pollution, particularly methylene blue, offering both environmental relief and economic benefits for sustainable wastewater treatment technologies.

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