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A Systematic Review on the Removal of Methylene Blue Dye from Water Using Bio-Adsorbent

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Abstract: The discharge of dye-contaminated wastewater from different industrial activities has become a significant environmental concern due to the toxicity, persistence, and complex chemical structure of synthetic dyes. Methylene blue (MB), a widely used cationic dye in textile, pharmaceutical, leather, and other industries, can adversely affect aquatic ecosystems and human health when discharged into the environment without adequate treatment. The present review provides a systematic overview of the removal of methylene blue from aqueous solutions using bioadsorbents, particularly those derived from agricultural and biological waste materials. Various conventional and advanced wastewater treatment methods, including chemical precipitation, coagulation–flocculation, membrane filtration, ion exchange, ozonation, electrochemical oxidation, and adsorption, are discussed with respect to their advantages and limitations. Particular emphasis is placed on the potential of agricultural residues, plant-based materials, microbial biomass, and other bio-waste-derived adsorbents as economical, renewable, and environmentally sustainable alternatives to commercial activated carbon. Furthermore, important operational parameters affecting adsorption performance, including solution pH, initial dye concentration, adsorbent dosage, and temperature, are critically discussed. These parameters influence surface charge, adsorption-site availability, mass transfer, and interactions between dye molecules and adsorbent surfaces. Overall, bioadsorption represents a promising approach for methylene blue removal, offering opportunities for agricultural waste valorization and sustainable wastewater management. Further research is required to improve adsorption capacity, regeneration efficiency, and large-scale applicability.

Keywords: *Methylene Blue; Bioadsorbents; Adsorption Efficiency; Sustainable Remediation.*

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I. INTRODUCTION

Dyes are complex organic aromatic compounds that are soluble in water. According to their origin they can be divided into natural and synthetic. Natural dyes are obtained from plant, animal, mineral, microbial or fungal sources. Plant based dyes are extracted from parts like leaves, twigs, flowers, bark, roots, fruits and stems. Synthetic dyes have brought about a revolution in the dye industry due to their low cost and excellent colour fastness, which has led to their wider use in commercial applications (M. Ismail et al.,2019). Synthetic dyes are categorised by their mode of application and chemical composition. Their chemical structure contains chromophores, groups of atoms that give colour by absorbing light at particular wavelengths. Common chromophores are azo, anthraquinone, triaryl methane, heterocyclic, indigo, nitroso, nitro and phthalein groups. Among them, the azo dyes are mainly used in industrial applications due to their simplicity of synthesis and the versatility of their molecular frameworks that enable a wide range of applications. They are the most widely used synthetic dyes (> 50% of total) in the world and are mainly used in the textile industry. They are red, orange and yellow in colour. Many dyes are hazardous and resistant to natural biodegradation (Kumar et al.,2026). Dyes are widely used in paper, plastic, rubber, leather, textile, cosmetics, food and pharmaceutical industries. The dye industry produces over 5000 tonnes of dye compounds each year. However, a huge amount of hazardous dye containing industrial effluents is discharged to the water systems which leads to the water pollution. Water pollution is the presence of biological, physical or chemical contaminants that negatively affect water quality and hence create risks to public health and safety. The chemistry of water is altered by the progressive destruction and disruption of the aquatic ecosystems by the dyes and their by-products in the effluent waste stream. This untreated discharge has caused severe damage in the past few years which consisted of 10–15% dyes in the effluent from textile, paper pro duction, tanning leather and food-processing industries and also from various dyes used for hair colouring products. Dyes are the most harmful contaminant since they are toxic, carcinogenic, mutagenic and nondegradable and are generally very stable for a long time in the environment. Methylene blue (MB) is a synthetic aromatic cationic dye. It is widely used in textile industry. Exposure to MB can cause skin damage and burning sensation of the eyes. Ingestion of MB can cause nausea,

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vomiting and adverse effects such as methemoglobinemia (Sharma et al., 2018). These colour contaminants have been treated by several physiochemical methods such as cloud point extraction, coagulation, membrane filtration, chemical oxidation, and various adsorption methods. Adsorption has been considered as a strong solution in terms of economic feasibility, easy availability and high efficiency (Silva et al. 2017b). Considering the above viewpoints biosorption is the most eco-friendly technique in an efficient manner to remediate dye contaminants (Sharma et al. 2018).

- *Methylene Blue Dye*

Methylene blue (MB) is a synthetic, heterocyclic cationic dye belonging to the thiazine class, with a molecular weight of 373.9 g/mol and a characteristic maximum absorption wavelength of approximately 665 nm. It is also known by its chemical name, Basic Blue 9, and has the molecular formula $C_{16}H_{18}ClN_3S$ (Farouk, 2018). Its molecular structure is illustrated in Figure 1. Owing to its cationic nature, MB can exhibit considerable toxicity and may pose adverse environmental and biological effects. It is extensively utilized in several industrial sectors, including textiles, rubber, plastics, leather processing, cosmetics, pharmaceuticals, and food manufacturing. Consequently, wastewater generated from these sources may contain residual MB, and even relatively low concentrations can contribute to visible colour contamination and deterioration of water quality (Modi et al., 2022).The characteristic blue colour of methylene blue originates from its conjugated molecular structure, particularly the delocalized π-electron system involving the central heterocyclic ring and its nitrogen- and sulphur-containing functional groups. Its optical characteristics are also effected by the pH of the surrounding medium, resulting in variations in colour intensity under different chemical conditions. The dye generally exhibits a lighter blue appearance under acidic conditions and progressively deeper blue shades as the pH increases. FTIR spectroscopy is commonly employed to investigate its molecular characteristics by identifying the principal functional groups and associated chemical bonds. Furthermore, the relatively stable chemical structure of MB makes it resistant to degradation through conventional treatment processes. However, photocatalytic treatment under suitable operating conditions can promote its decomposition and eventual mineralization into simpler inorganic products, including carbon dioxide and water (Onyango et al., 2026).

- *Health Impact of Methylene Blue Dye*

Methylene blue (MB) is a widely used synthetic cationic dye with applications in clinical medicine, where it serves as a colouring agent, diagnostic indicator, and antimicrobial compound. Despite its therapeutic and industrial applications, excessive exposure to MB may cause adverse toxicological effects. various studies have associated high or prolonged exposure to this dye with potential health complications, including haemolytic anaemia, hyperbilirubinemia, pulmonary toxicity, acute renal impairment, chromosomal abnormalities, and mutagenic effects. Cytotoxic effects have also been observed in human SK-N-MC neuroblastoma and U-373 MG astrocytoma cell lines, with adverse cellular effects reported even at microgram-level concentrations. The oral median lethal dose (LD_{50}) of MB has been estimated at approximately 1,180 mg kg^{-1}. Furthermore, its physiological effects are dose-dependent, particularly under endotoxemic conditions. Low and moderate doses have been reported to increase arterial blood pressure, whereas higher doses may aggravate cardiovascular disturbances, including systemic hypotension and myocardial depression. High-dose exposure can also increase renal and mesenteric vascular resistance, potentially reducing blood flow and impairing gas exchange. In addition, MB administration may produce temporary greenish-blue discolouration of urine and bluish staining of the skin and mucous membranes. These potential toxicological effects highlight the importance of effectively removing methylene blue from contaminated wastewater before its discharge into the environment. Exposure to high concentrations of methylene blue (MB) may produce several adverse physiological effects, including increased vascular resistance in the renal and mesenteric circulations, reduced blood flow, and impaired pulmonary gas exchange. MB administration may also result in temporary greenish-blue discolouration of urine and bluish staining of the skin and mucous membranes. Furthermore, a clinical case involving a female breast cancer patient who underwent sentinel lymph node biopsy reported localized tissue damage, followed by skin necrosis and dry gangrene after the peritumoral administration of MB. These complications were attributed to the dye's local tissue-reactive properties (Modi et al., 2022). Beyond its potential effects on human health, the environmental persistence of MB is a concern because of its toxicity, resistance to biodegradation, and potential adverse impacts on aquatic ecosystems. Exposure to contaminated water may pose risks to human health, while the discharge of dye-containing effluents can negatively affect aquatic organisms and overall water quality. Owing to its intense coloration and high molar absorptivity (8.4×10^4 L mol^{-1} cm^{-1} at 664 nm), MB significantly reduces light penetration into water bodies, potentially interfering with photosynthetic activities in aquatic environments. Despite these environmental and toxicological concerns, MB continues to be extensively used as a colouring agent in biomedical, pharmaceutical, textile, and food-processing industries. Its widespread industrial application and persistence in wastewater make the development of effective removal and treatment technologies particularly important (Onyango et al., 2026).

- *Treatment Methods for MB's Removal*

Appropriate treatment of dye-contaminated wastewater is essential for reducing environmental pollution and protecting human health. Conventional industrial wastewater treatment generally consists of four major stages: preliminary, primary, secondary, and tertiary treatment (Hamad & Idrus, 2022). Preliminary treatment involves the removal of coarse and unwanted materials, such as large debris, grit, suspended particles, oil, and grease, primarily through screening and grit separation. Primary treatment focuses on eliminating settleable and floating impurities through processes such as sedimentation, flotation, and skimming. Secondary treatment primarily employs biological methods in which microorganisms break down dissolved and

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colloidal organic pollutants. The final stage, tertiary treatment, is designed to eliminate residual contaminants using advanced physical, chemical, and biological techniques, including membrane filtration, adsorption, ion exchange, ozonation, and advanced oxidation processes (Saratale et al., 2021). Adsorption has found considerable attention as an effective approach for removing synthetic dyes from wastewater. In recent years, environmentally sustainable adsorbents derived from agricultural residues and biological materials have emerged as potential alternatives to conventional commercial activated carbon (CAC). These include plant-based materials obtained from leaves, bark, fruit peels, and other lignocellulosic residues, along with microbial biosorbents such as fungi, algae, and bacterial biomass. Furthermore, advanced carbon-based materials, including graphene, carbon nanotubes, and their derivatives, have demonstrated considerable potential for wastewater decolorization (Hamad & Idrus, 2022). Activated carbon is generally produced through the carbonization and subsequent activation of carbon-rich raw materials, including coal, bamboo, wood, charcoal, seeds, and agricultural residues such as coconut shells. Its highly synthesized porous structure and large specific surface area contribute to its adsorption efficiency. Reported dye removal efficiencies range from 93.6–97.7% for activated carbon and 94.4–99.0% for microalgae-based treatment systems. However, the replacement of commercial activated carbon (AC) with economical and sustainable alternatives requires further investigation into raw material selection, carbonization and activation conditions, surface characteristics, adsorption capacity, and regeneration potential. Therefore, the utilization of agro-waste-derived adsorbents represents a promising strategy for developing cost-effective and environmentally sustainable dye-removal technologies.

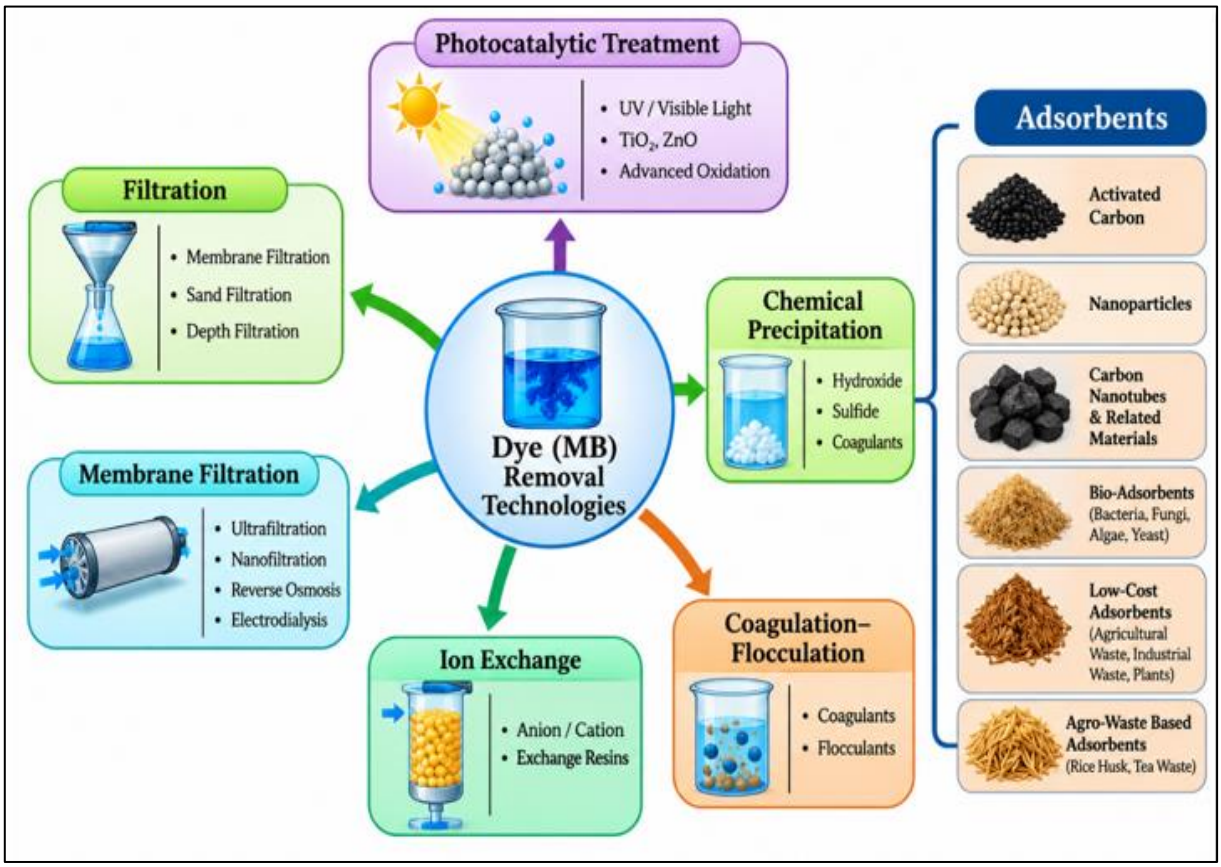


Fig 1 Classification of Different Treatment Technology of Methylene Blue Dye from Water.

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Table 1 Benefits and Drawbacks of Wastewater Treatment Technologies for Methylene Blue (MB) Removal

Treatment technology	Benefits	Drawbacks	Reference
Ion exchange	High removal efficiency; adsorbent can be regenerated.	pH-sensitive; regeneration is costly and produces sludge.	Crini, G. (2006).
Electrochemical oxidation	Rapid dye degradation with minimal chemical addition.	High electricity costs and possible sludge formation.	Singh, K., & Arora, S. (2011).
Advanced oxidation processes	Rapid dye degradation; reduces organic pollutants and COD.	High operating costs; may produce harmful intermediates.	(H. N., & Idrus, S. 2022).
Chemical precipitation	Simple, economical, and effective for high pollutant loads.	High chemical consumption and sludge generation.	Crini, G., & Lichtfouse, E. (2019).
Ozonation	Fast decolorization and effective disinfection.	High operating costs and potential by-product formation.	(Holkar et al.,2016)
Fenton reagents	Rapid oxidation and effective dye removal.	Requires acidic pH and produces iron-containing sludge.	(H. N., & Idrus, S. 2022).
Coagulation–flocculation	Simple, effective, and suitable for large-scale treatment.	Produces sludge and increases dissolved solids.	Foo, K. Y., & Hameed, B. H. (2010).
Reverse osmosis	Excellent dye and salt removal; produces high-purity water.	High energy demand, membrane fouling, and concentrated waste.	Foo, K. Y., & Hameed, B. H. (2010).
Biological treatment (aerobic and anaerobic)	Low-cost, environmentally friendly, and potentially effective dye degradation.	Slow treatment; efficiency depends on dye biodegradability and operating conditions.	Foo, K. Y., & Hameed, B. H. (2010).
Ultrafiltration and nanofiltration	Effective dye separation and high-quality treated water.	Membrane fouling, high pressure, and replacement costs.	(H. N., & Idrus, S. 2022).
Adsorption	Simple, efficient, and suitable for various dyes; bioadsorbents can be inexpensive and renewable.	Adsorbent saturation, regeneration requirements, and disposal of dye-loaded materials.	(H. N., & Idrus, S. 2022).

II. FACTORS INFLUENCING ADSORPTION PERFORMANCE

The Potential of dye removal through adsorption is governed by several intrinsic characteristics of the adsorbent as well as the operating conditions of the treatment system. Important adsorbent properties, such as specific surface area, pore structure, porosity, surface functional groups, and chemical stability, determine the availability and accessibility of active adsorption sites. These characteristics directly influence the interaction between dye molecules and the adsorbent surface, thereby affecting its overall adsorption capacity. In addition to the physicochemical properties of the adsorbent, various operational parameters play a significant role in determining the adsorption performance. These include solution pH, temperature, initial dye concentration, contact time, and adsorbent dosage. Changes in these conditions can influence surface charge, electrostatic interactions, mass transfer, and the availability of active binding sites. Therefore, systematic optimization of these parameters is essential to achieve maximum dye removal efficiency and improve the economic feasibility of adsorption-based wastewater treatment. A comprehensive understanding of these factors is particularly important for developing efficient, sustainable, and scalable adsorbent materials for industrial wastewater management (Fakunmoju et al., 2025).

- *Effect of pH*

Solution pH is one of the most important operational parameters influencing dye adsorption because it determines the surface charge of the adsorbent and the ionic characteristics of dye molecules. These changes regulate the electrostatic attraction or repulsion between the adsorbent and the dye, thereby affecting the overall removal efficiency. Under acidic conditions, protonation of the adsorbent surface generates positively charged sites, which generally favour the adsorption of anionic dyes through electrostatic attraction. However, these conditions may limit the uptake of cationic dyes due to electrostatic repulsion. In contrast, alkaline conditions promote the deprotonation of surface functional groups, resulting in a negatively charged adsorbent surface that enhances the removal of positively charged dyes, including methylene blue (Chikri et al., 2020). The pH-dependent behaviour of adsorption can also be controlled by adjusting the solution chemistry using acids or alkalis. For instance, hydrochloric acid (HCl) is commonly used to establish acidic conditions and facilitate surface protonation, whereas sodium hydroxide (NaOH) increases solution pH and promotes surface deprotonation. Consequently, alkaline conditions may favour cationic dye adsorption, while acidic conditions generally enhance anionic dye removal, depending on the adsorbent's point of zero charge and surface chemistry (Fakunmoju et al., 2025).

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➢ *Effect of Dye Concentration*

The initial concentration of dye in wastewater is an important factor governing the adsorption process and its overall efficiency. It determines the concentration between the liquid phase and the adsorbent surface, thereby influencing the rate of mass transfer and the quantity of dye molecules adsorbed. Generally, the adsorption capacity increases with the increase in initial dye concentration, due to the higher driving force for the transfer of dye molecules to the available active sites. However, as the adsorption process progresses, these sites gradually become occupied, eventually approaching saturation. Beyond a certain concentration, the limited availability of unoccupied adsorption sites may restrict further dye uptake, resulting in a plateau in adsorption capacity and potentially reducing the percentage removal efficiency (Dutta et al., 2021).

➢ *Effect of Adsorbent Dosage*

Adsorbent dosage is an important operational parameter that directly affects the efficiency of dye removal from aqueous solutions. Increasing the amount of adsorbent generally provides a greater number of accessible active sites and a larger overall surface area for dye molecule attachment, thereby improving the percentage removal of contaminants. However, despite the increase in removal efficiency, the adsorption capacity expressed per unit mass of adsorbent may decline at higher dosages. This reduction is primarily associated with the availability of excess adsorption sites that remain unoccupied due to an insufficient quantity of dye molecules in the solution. Additionally, at elevated adsorbent concentrations, particle aggregation may occur, leading to a reduction in the effective surface area and limiting the accessibility of adsorption sites. Such aggregation can also interfere with the diffusion of dye molecules towards the adsorbent surface, ultimately influencing the overall adsorption performance (Popa et al., 2021).

➢ *Effect of Temperature*

Temperature shows a significant role in determining the adsorption behaviour and removal efficiency of dyes from water. Its effect is primarily associated with the thermal characteristics of the adsorption process, which may be either endothermic or exothermic (Fakunmoju et al., 2025). In endothermic adsorption, an increase in temperature generally enhances the adsorption capacity by facilitating the interaction between dye molecules and the adsorbent surface. Elevated temperatures may also improve molecular mobility, accelerate diffusion, and increase the accessibility of active adsorption sites, thereby promoting dye uptake (Sharma et al., 2021). In contrast, exothermic adsorption generally exhibits a reduction in adsorption capacity as temperature rises. This behaviour occurs because higher thermal energy can weaken the attractive forces between dye molecules and the reactive sites of the adsorbent, favouring desorption and reducing the overall adsorption efficiency (Fakunmoju et al., 2025). Therefore, investigating the influence of temperature is essential for understanding the adsorption mechanism and identifying optimum operating conditions for effective dye removal.

III. CONCLUSION

The present review highlights the environmental challenges associated with methylene blue contamination in aqueous environments and evaluates the potential of bioadsorption as a sustainable approach for its removal. Methylene blue is a widely used synthetic cationic dye that exhibits considerable chemical stability and resistance to conventional biodegradation. Its uncontrolled discharge into aquatic environments can deteriorate water quality, reduce light penetration, disturb photosynthetic activities, and pose potential risks to aquatic organisms and human health. Therefore, the effective treatment of dye-containing wastewater is essential for environmental protection. Various physicochemical, chemical, biological, and advanced treatment technologies have been developed for methylene blue removal. Although techniques such as membrane filtration, ozonation, electrochemical oxidation, ion exchange, and advanced oxidation processes can achieve effective dye removal, their applications may be restricted by high operational costs, energy requirements, chemical consumption, sludge generation, and membrane fouling. In comparison, adsorption offers a relatively simple, efficient, and adaptable treatment approach. In particular, bioadsorbents prepared from agricultural residues, plant leaves, bark, fruit peels, and microbial biomass have considerable potential as low-cost and environmentally friendly alternatives to commercial activated carbon. The adsorption performance of these materials is strongly influenced by solution pH, dye concentration, adsorbent dosage, temperature, surface characteristics, and the availability of functional groups and active adsorption sites. Appropriate optimization of these parameters is necessary to improve dye removal efficiency and adsorption capacity. Moreover, the utilization of agricultural waste as an adsorbent can contribute to waste minimization, resource recovery, and the development of circular economy approaches. Despite the promising efficiency of bioadsorbents, further investigations are necessary to improve their adsorption capacity, mechanical and chemical stability, regeneration, and reusability. Future research should also focus on continuous-flow treatment systems, real industrial wastewater applications, economic assessment, and large-scale implementation. Overall, agricultural waste-derived bioadsorbents represent a promising, economical, and sustainable alternative for methylene blue removal and can contribute significantly to the advancement of environmentally responsible wastewater treatment technologies.

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