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Sustainability of Chemically Treated Waste-Derived Adsorbents for Dye Removal: A Review

Saiful Azhar Saad[1,*], Khairuddin Md. Isa[1,2], Mohd Nazree Derman[2], Farizul Hafiz Kasim[1,2], Naimah Ibrahim[3], Mohd Aizudin Abd. Aziz[4]

[1] Faculty of Chemical Engineering & Technology, Kompleks Pengajian Kejuruteraan Jejawi 3, Universiti Malaysia Perlis, 02600 Jejawi, Arau, Perlis, Malaysia
[2] Centre of Excellence for Biomass Utilization, Kompleks Pengajian Kejuruteraan Jejawi 3, Universiti Malaysia Perlis, 02600 Jejawi, Arau, Perlis, Malaysia
[3] Faculty of Civil Engineering & Technology, Kompleks Pengajian Kejuruteraan Jejawi 3, Universiti Malaysia Perlis, 02600 Jejawi, Arau, Perlis
[4] Faculty of Chemical and Natural Resources Engineering, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), 26300 Kuantan, Pahang, Malaysia

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ABSTRACT

Activated carbon is widely used in industrial wastewater treatment due to its high efficiency. However, it is costly and typically derived from non-renewable sources. This has led to growing interest in the utilisation of waste-derived adsorbents as a more sustainable alternative for wastewater treatment, particularly for organic pollutants such as dyes. Early studies explored the applications of waste materials without any chemical modifications. However, such approaches resulted in low adsorption performances and potentially secondary pollution, such as high chemical oxygen demand and biological oxygen demand in treated effluent. While numerous studies have demonstrated that chemical treatment can significantly enhance the performance of waste-derived adsorbents, a comprehensive evaluation of their sustainability remains limited. This review critically examines recent advances in waste-based adsorbents, with a particular focus on the role of chemical treatment methods, including acid and alkali treatments, in improving adsorption capacity and selectivity. The sustainability of chemically treated adsorbents is assessed by considering key factors, such as raw material availability, chemical consumption, regeneration potential, and environmental implications associated with the preparation and use of the adsorbent. Additionally, the review examines the trade-offs between enhanced adsorption performance and the environmental impacts associated with chemical modification. Current challenges, knowledge gaps, and future research directions are highlighted, emphasising the development of balanced and environmentally responsible treatment strategies. This review aims to guide the rational design of sustainable waste-derived adsorbents for practical wastewater treatment applications.

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[*] *Corresponding author.*
E-mail address: saifulazhar@unimap.edu.my

1. Introduction

The demand for clean water has significantly increased, driven by rapid urbanisation and industrialisation. This has strained existing water resources due to increased pollution and inadequate water treatment systems [1]. Industrial wastewater consists of organic and inorganic substances, as well as highly toxic and hazardous substances such as dyes and heavy metals. Dyes are widely used to impart colour to various industrial products, with the textile industry being the largest consumer of these substances. It is estimated that nearly 700,000 tons of synthetic dyes are produced annually, with approximately 50% of the dyes lost during processing [2]. Due to the extensive use of dyes, a considerable volume of coloured wastewater is generated, which contributes to the degradation of water bodies and severe aquatic pollution. Furthermore, the molecular structure of these dyes makes them carcinogenic, mutagenic, and highly toxic [3].

Due to the detrimental effects of dye-contaminated wastewater on the environment, human, and aquatic life, it is crucial to have a comprehensive understanding of the impact and behaviour of dyes [4]. Parida *et al*., [5] discussed the effects of dye contamination on aquatic ecosystems and human health, alongside sustainable remediation strategies. Lellis *et al*., [3] also reviewed the impact of dye contamination on health and the environment, highlighting the potential of living organisms for the bioremediation of dye pollution. Al-Tohamy *et al.,* [2] reviewed the ecotoxicological effects of dye contamination from both biological and environmental perspectives. They also compared various remediation strategies for dye contamination, including adsorption and biological methods.

In the past, discharges of dyes received limited attention regarding their environmental impacts, and there was very limited regulation governing the accepted limits of dyes in industrial effluents. Early wastewater treatment systems relied on water purification methods such as equalisation and sedimentation [6]. The introduction of the United Nations Sustainable Development Goals, the establishment of discharge standards, and increasing public concern have driven the development of more advanced technologies, including dye-degrading filter beds and the activated sludge process, to treat dye-contaminated wastewater. Despite these advancements, the adoption of advanced technologies remains constrained by economic and operational factors [7]. Generally, dye removal methods can be categorised into three main types: chemical, physical, and biological treatments. Figure 1 provides an overview of dye-contaminated wastewater generated by industrial activities and illustrates how adsorption with chemically treated waste-derived adsorbents can mitigate environmental discharge, while highlighting key sustainability considerations.

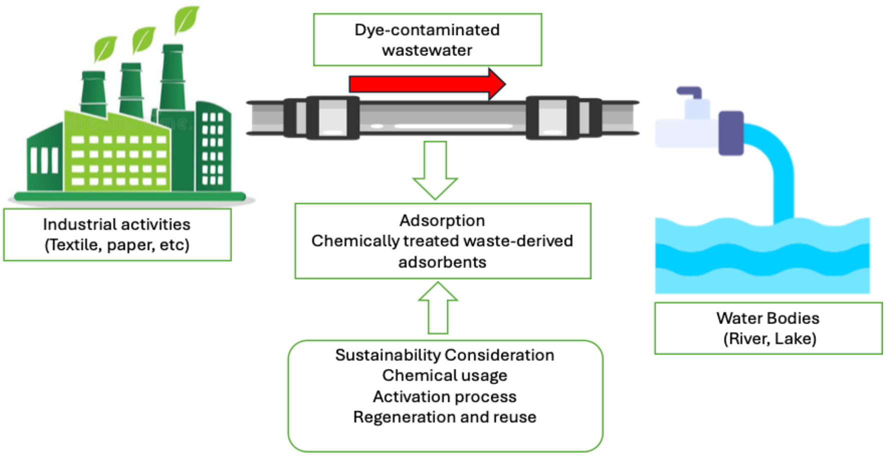

Fig. 1. Overview of dye-contaminated wastewater generation from industrial activities and its mitigation through adsorption using chemically treated waste-derived adsorbents

2. Current Treatments for Dye Removal

Due to their detrimental effects, dyes must be properly treated before being discharged into water bodies. Figure 2 depicts the classification of current methods for dye removal.

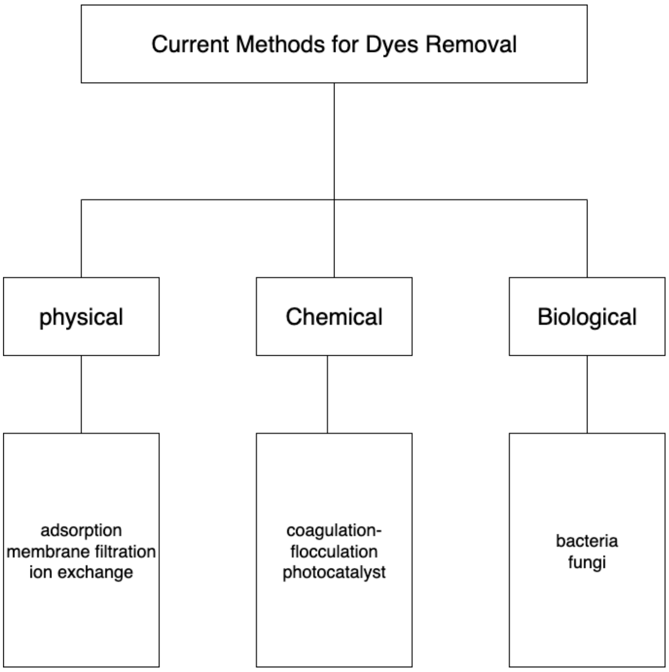

Fig. 2. Classification of current methods for dye removal

2.1 Physical Treatment

Numerous physical treatment methods have been employed to remove dyes from wastewater. These methods include adsorption, ion exchange, and membrane filtration. These treatments are commonly associated with their ability to treat a wide variety of dyes, their simple design, and cost-effectiveness. However, their wider application is often hindered by drawbacks such as the generation of secondary sludge, the need for adsorbent regeneration, and limited ability to treat large volumes of wastewater. Furthermore, optimum performance typically requires specific optimum conditions.

Lu *et al.,* [8] investigated the use of anion- and cation-exchange magnetic microbeads for the removal of the basic dye (Crystal Violet) and the acid dye (Acid Green 9) from single- and mixed-systems. Their study found that both individual and combined adsorbents effectively removed dyes via heterogeneous diffusion. Similarly, Türk *et al.,* [9] utilised a membrane derived from modified sugar beet pulp by-products for the removal of Basic Yellow 51, achieving an adsorption capacity of 200 mg/g.

2.2 Chemical Treatment

Conventional chemical treatments for dye removal include coagulation-flocculation, photocatalysis, and chemical oxidation. These methods are usually more expensive than physical and biological treatments, often due to high energy consumption, the use of large amounts of chemicals, the need for properly set-up systems, and the production of hazardous by-products during treatment.

In coagulation, impurities such as non-settling solids and coloured substances are removed by adding coagulants, such as aluminium sulphate (alum), ferric chloride, or polyaluminum chloride. These coagulants neutralise the surface charges on suspended particles, destabilising them and forming small aggregates. Following coagulation, flocculation promotes the growth of these small particles into larger, more settleable flocs through gentle mixing. This step allows particles to collide and bind, forming heavier aggregates that can be more easily separated from the liquid phase by sedimentation or filtration. A study by Ihadadden *et al.,* [10] employed bentonite and *Opuntia ficus-indica* powder (OFIP) as natural alternatives to conventional coagulant and flocculant agents. The combination of B-OFIP achieved Methylene Blue (MB) removal of 98.25%, outperforming alum/OFIP (58.14%) and B-polymer (97.7%).

2.3 Biological Treatment

In biological treatment, organisms such as bacteria, fungi, algae, or mixed microbial consortia are employed to degrade, transform, or mineralise dye molecules and other organic pollutants in industrial wastewater. These systems harness metabolic activity to reduce colour, chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids, and turbidity. Biological approaches are generally more sustainable than chemical or physical processes because they require fewer chemical reagents, produce less sludge, demand lower energy input, and produce non-toxic by-products.

Recent studies have reinforced the potential of biological systems. For example, *Bacillus* sp. React3, which is produced by lignin peroxidase, achieved substantial degradation of MB under optimal conditions [11]. Mixed bacterial cultures have been successfully applied to the decolourisation and detoxification of Di-Azo Dye Direct Red 81, even under harsh environmental conditions [12].

Although physical and chemical methods demonstrate high efficiency, they are often associated with high costs, require high energy, and produce sludge as a by-product [13]. Additionally, while biological treatments using selective strains of bacteria and fungi capable of degrading organic dyes are promising eco-friendly approaches for dye removal, they remain in the early stages of development and lack available information regarding their application [14].

3. Adsorption

Adsorption is one of the most widely employed physical methods for dye removal due to its high efficiency, simplicity, and minimal production of harmful by-products. It involves the accumulation of dye molecules at the solid–liquid interface and is widely used due to its simplicity and efficiency. Physisorption occurs via weak van der Waals forces and is reversible, whereas chemisorption involves stronger electron-exchange interactions and is generally irreversible.

Commercial activated carbon (CAC) is commonly produced from coal, coconut shells, lignite, or wood. Its high surface area and well-developed porosity make it a standard benchmark material in adsorption studies. Generally, there are two types of activation methods: chemical and physical. Physical activation requires higher temperatures and longer activation times than chemical activation. However, chemical activation necessitates thorough washing because chemical agents are used. The activation process widens pore openings and enlarges existing pores, resulting in a net increase in surface area. Previous studies have frequently employed CAC for dye removal, as demonstrated by Dehmani [15] for Methyl Orange adsorption and by Kannan and Sundaram [16], who compared CAC with other bio-based adsorbents for MB removal. Rafatullah *et al.,* [17] published a review of the effectiveness of CAC for MB removal.

The exceptional attributes of CAC lie in its remarkable efficiency and the ability to operate and produce at a low cost. Over the past few years, significant progress has been made in understanding and utilising adsorption as a powerful and adaptable technique. Although widely used, the production cost of activated carbon remains a significant drawback, particularly due to its non-renewable precursors [18]. Furthermore, chemical agents are required to enhance their effectiveness in removing inorganic substances. Consequently, its high cost and limited efficiency have hindered its widespread application, especially for small-scale industries.

Recently, there has been an increasing emphasis on researching alternative adsorbents to replace costly activated carbon. Attention has shifted towards adsorbents with high binding capacities that can effectively remove dyes from contaminated water at lower costs. Natural materials that are abundantly available, as well as industrial by-products or agricultural biomass, have demonstrated their potential as inexpensive adsorbents [19]. Guru *et al*., [20] reviewed the removal of textile dyes using hydroxyapatite-based adsorbents, focusing on their surface functionality and adsorption mechanism. Nath *et al.,* [21] examined the performance of chitosan-based adsorbents from the perspectives of adsorption mechanism, regeneration, and predictive models. The environmental sustainability perspective on the application of chitosan-based adsorbents has been reviewed and reported by Patel and Upparuli [22]. Table 1 provides a general overview of the adsorption capacities of different types of waste materials and their chemical activating agents.

4. Sustainability of Chemically Treated Waste-Derived Adsorbents

The application of waste-derived materials as adsorbents has attracted considerable attention from researchers as a sustainable method for dye removal in industrial processes. Employing these materials can reduce reliance on non-renewable CAC and promote resource recovery and waste minimisation. In addition, these waste materials are readily available at no cost and possess a variety of surface chemistries that can enhance adsorption performance. Over the past 20 years, waste materials have been used without undergoing chemical activation. However, it has been found that using waste materials without chemical activation results in high COD and BOD in the effluents [23]. This has led to research on the chemical activation of waste materials. The chemical activation process commonly involves the use of strong acids and alkalis. The typically employed strong acids include phosphoric acid, sulphuric acid, and hydrochloric acid, while the commonly used strong alkalis are sodium hydroxide and potassium hydroxide.

The study by Saad *et al.* showed that chemical activation not only improves the COD and BOD of the effluent but also enhances removal efficiency and adsorption capacity by increasing porosity and introducing oxygen-containing functional groups [13]. While chemical activation improves the performance of adsorbents, it also raises sustainability concerns about chemical handling and consumption, as well as the generation of chemical residues during activation. The environmental benefits associated with waste-derived precursors may be partially offset by the intensive use of activating agents and the repeated washing cycles required to neutralise residual chemicals [24, 25]. In addition, the disposal or recovery of spent chemical solutions and wash water contributes to secondary environmental burdens. From a sustainability perspective, adsorption capacity alone is insufficient to justify chemical modification, particularly when high-performance gains are marginal compared to untreated or mildly treated materials.

Regeneration and reusability are critical indicators of sustainability for chemically treated adsorbents. Many studies report high initial dye removal efficiencies; however, adsorption performance often declines significantly after multiple regeneration cycles due to pore blockage, structural degradation, or loss of surface functional groups. Adsorbents that require harsh regeneration conditions further increase chemical and energy demands, undermining their environmental advantages [26]. Consequently, long-term performance and regeneration efficiency should be prioritised alongside initial adsorption capacity.

To achieve sustainable implementation, future research should focus on optimising chemical treatment intensity, exploring greener activation strategies, and standardising sustainability assessment metrics. Evaluations should incorporate chemical usage, energy input, adsorbent lifespan, regeneration efficiency, and secondary waste generation. Emphasising balanced performance rather than maximum adsorption capacity will be essential for the practical and environmentally responsible deployment of chemically treated waste-derived adsorbents in wastewater treatment applications.

Table 1
Sustainability considerations for chemically treated waste-derived adsorbents

Aspect	Benefit	Sustainability Concerns
Waste materials	Low cost, abundantly available	Varying composition and structure
Acid/alkali activation	High surface area, improved porosity and surface charge	Generation of acidic/alkaline wastewater, handling of corrosive chemicals, high chemical consumption
Adsorption capacity	High adsorption capacity	Often prioritised over sustainability considerations
Regeneration	Reduced material requirements, waste minimisation	Performance loss over cycles, chemical usage

Chemically-treated waste-derived adsorbents have demonstrated considerable potential for dye removal; however, adsorption performance alone does not provide a comprehensive picture of their environmental sustainability [26]. The preparation of these materials commonly involves chemical activation using acids or alkalis, alongside energy-intensive processes such as heating, washing, and drying. Although these treatments enhance surface properties and adsorption efficiency, they may also introduce additional environmental burdens that are often overlooked in laboratory-scale studies.

Life cycle assessment (LCA) offers a practical framework for evaluating trade-offs by accounting for the environmental impacts associated with each stage of an adsorbent's life cycle, from raw material sourcing and chemical activation to use, regeneration, and final disposal [27]. Unlike conventional performance indicators, LCA integrates resource consumption, energy demand, emissions, and waste generation. When applied to chemically-treated waste-derived adsorbents, this approach enables a more balanced assessment of whether performance improvements justify the environmental costs of chemical modification [28].

Despite its relevance, LCA is still rarely applied in adsorption studies focused on dye removal. Many studies prioritise reporting the maximum adsorption capacity under optimised conditions, with limited attention to chemical consumption, washing requirements, or the generation of secondary waste streams during adsorbent preparation [29]. The lack of consistent sustainability assessments limits meaningful comparisons across materials and complicates efforts to scale up promising laboratory results.

Incorporating LCA into future research would therefore strengthen the evaluation of waste-derived adsorbents and support more informed material and process selection [27]. By identifying key environmental hotspots and performance trade-offs, LCA can guide the development of adsorption systems that achieve effective dye removal while remaining environmentally responsible. Such integration is essential for advancing chemically-treated waste-derived adsorbents towards practical and sustainable industrial wastewater treatment applications [30].

5. Conclusions

The increasing discharge of dye-contaminated wastewater from industrial activities continues to pose significant environmental and health challenges, necessitating the development of effective and sustainable treatment strategies. Among the available treatment methods, adsorption has emerged as a promising approach due to its operational simplicity, high removal efficiency, and adaptability to a wide range of dye pollutants. In recent years, considerable attention has been directed towards the use of waste-derived materials as low-cost adsorbents, offering opportunities for waste valorisation and reduced reliance on CAC.

This review highlights that chemical treatment and activation of waste-derived adsorbents can substantially enhance adsorption performance by improving surface area, pore structure, and functional group availability. However, improved adsorption capacity alone is insufficient to justify chemical modification, particularly when sustainability considerations are neglected. The use of acids, alkalis, and other activating agents introduces additional environmental burdens related to chemical consumption, activation processes, regeneration requirements, and potential secondary waste generation.

From a sustainability perspective, the long-term applicability of chemically treated waste-derived adsorbents depends not only on their initial dye removal efficiency but also on their regeneration potential, durability across multiple adsorption cycles, and overall environmental footprint. Current studies often lack standardised evaluation criteria, which limits meaningful comparisons between materials and hinders large-scale implementation.

Future research should focus on balancing adsorption performance with environmental responsibility by optimising activation processes, minimising chemical usage, and improving regeneration efficiency. Integrating sustainability assessments into adsorbent design and evaluation will be essential for advancing the practical application of waste-derived adsorbents as viable, environmentally responsible solutions for industrial dye wastewater treatment.

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