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Removal of Industrial Dyes using Biochar Derived from Tender Coconut Waste: A Review

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***Abstract*— The discharge of wastewater containing dyes, which is broadly produced by the textile, leather, and paper industries, is hazardous to both aquatic life and humans because of the toxicity of synthetic dyes and the complexity of dyes. Conventional treatment methods are expensive, are not effective in eradicating dyes, and generate secondary pollutants. Dye removal via adsorption, particularly using sustainable adsorbents, is a reliable process. The carbon-based product of biomass pyrolysis under low oxygen concentration has gained interest as an alternative to activated carbon; this is known as biochar. This review discusses the application of biochar prepared using tender coconut waste as an adsorbent for the removal of industrial dyes. This study examined the structure and benefits of tender coconut waste as a biochar feed and industrial dye, and its effects on the environment. A comparison of dye removal methods indicated the effectiveness and sustainability of biochar-based adsorption. The physicochemical characteristics of tender coconut waste biochar affecting dye adsorption, including surface area, pore structure, functional groups, and surface charge, were studied with reference to adsorption mechanisms such as electrostatic attraction, π–π interactions, and pore filling. The benefits of tender coconut waste biochar in terms of its economic viability and circular economy were evaluated. This review concludes that tender coconut waste biochar is a sustainable option for the removal of industrial dyes, which will be included in the elaboration of the design of scalable dye removal systems.**

***Index Terms*— Biochar, tender coconut waste, dye removal, adsorption, low-cost adsorbent, economics.**

I. INTRODUCTION

The rapid growth of industries has led to the release of dye-contaminated effluents from the textile, leather, paper, printing, cosmetics, and pharmaceutical industries. Many dyes used in industries are discharged into wastewater treatment systems. Dyes create a strong coloration of water, decrease light penetration, and interfere with the photosynthesis of aquatic organisms, even at low concentrations, which affects the levels of dissolved oxygen and the ecological balance. Industrial dyes have been developed to be chemically stable, resistant to oxidation and light, and highly fiber affine. These characteristics render dyes recalcitrant and non-biodegradable. Many dyes and their byproducts are toxic, mutagenic, or carcinogenic and pose a threat to aquatic life and human health because of bioaccumulation.

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Newly introduced environmental regulations necessitate the employment of efficient methods for treating wastewater containing dyes [1], [2]. Removal techniques can be physical, chemical, or biological, such as coagulation-flocculation, advanced oxidation, membrane filtration, and biological degradation. However, they have some drawbacks, such as high cost and secondary waste production. The adsorption technique has turned out to be a productive procedure owing to its simplicity and adaptability. Although commercially available activated carbon is functional, it is very expensive, thus limiting its application on a large scale [3]. Biochar is also a low-cost, sustainable alternative adsorbent. Biochar is a high-carbon porous substance created by biomass pyrolysis in the presence of a limited quantity of oxygen. Its characteristics can be customized based on the feedstock choice and dye adsorption production conditions. Coconut waste has the potential to be used as biochar for wastewater treatment [4]. Coconut waste is typically disposed of as tender coconut waste, which is produced in large quantities in tropical areas. This waste can be transformed into biochar, which is an effective dye adsorbent, to support waste management [5]. In this review, biochar made from tender coconut waste is considered an industrial dye removal medium, with a review of the benefits of the feedstock, dye effects, treatment, biochar characteristics, and economic considerations for scale-up. This review cites important literature on research, methods of modification, and techno-economic for future research.

II. Tender Coconut Waste used as A Feedstock

Tender coconut waste, such as green husks, fronds, shell fragments, and leftover endosperm after water extraction, is produced during the harvesting and processing of tender coconuts in tropical and coastal regions. These remains are normally disposed of by dumping or burning, resulting in pollution. These wastes are not well exploited in coconut producing areas. By transforming this waste into biochar, sustainable management and the creation of value-added products can be used in environmental remediation. The feedstock contains good fixed carbon at moderate to high pyrolysis temperatures producing a more stable carbon-rich biochar [5], [6], [7]. Figure 1 shows the conversion of tender coconut waste is converted to biochar through pyrolysis for dye removal. The tender coconut biomass components possess unique physicochemical characteristics; therefore, the biochar properties can be customized to a particular pollutant. The desired high surface area and chemistry of biochars can be generated through the proper selection of feedstock and pyrolysis techniques for dye removal. Coconut waste that has been wasted is mostly lignocellulosic in nature and includes cellulose, hemicellulose, and lignin, with small amounts of extractives and ash. The high lignin content enhances char and stability, and cellulose promotes the formation of pores. The low ash level is favorable for adsorption because excess ash may decrease efficiency, as shown in Table I. Coconut shell and husk biochar exhibit mechanical strength and an efficient microporous structure suitable for dye adsorption under optimal conditions [8], [9], [10].

Table I. Tender Coconut Waste as a Biochar Feedstock: Composition, Properties, and Relevance

Biomass Component	Major Chemical Composition	Key Physicochemical Features	Relevance to Biochar Performance	References
Green coconut husk	Cellulose (35-45%), hemicellulose (20-30%), lignin (25-30%)	Fibrous, low ash, oxygen-rich	Enhances surface functional groups and mesoporosity	[7], [9]
Tender coconut shell	High lignin (45-50%), fixed carbon	Dense, rigid structure	Produces mechanically stable biochar with high microporosity	[6], [11]
Coconut fronds	Cellulose-rich biomass	Lightweight, porous precursor	Promotes pore development during pyrolysis	[12]
Residual endosperm	Organic carbon, volatile matter	Easily decomposable	Improves char yield at lower temperatures	[13], [14]

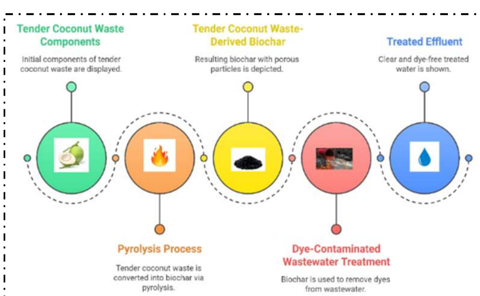

Figure 1. Conversion of tender coconut waste to biochar via pyrolysis for industrial dye adsorption from wastewater.

III. TYPES OF DYES AND THEIR EFFECTS

Industrial dyes are a wide range of synthetic organic compounds designed to provide permanent color staining to clothing and other substances. The most widely used dye is the azo dyes, which is characterized by one or more azo (-N=N-) bonds between aromatic rings. These stains are remarkably stable normal environmental conditions; however, in reductive conditions, they can break down into aromatic amines, some of which are known to be both toxic and carcinogenic [15]. Table II gives an overview of some of the major types of dyes, their industrial applications, and associated environmental and health hazards. As mentioned, many dyes are highly degradable and toxicity resistant, which is why it is important to eliminate dyes efficiently before the wastewater is released. Cationic dyes including methylene blue and malachite green, have a positive charge in aqueous solutions and are widely used for dyeing textiles, coloring paper, and as biological stains. Although they are commonly used, these dyes are very toxic to aquatic organisms even in low concentrations, and may have severe physiological and genetic adverse effects [16], [17]. Anionic dyes, also known as acid dyes, include negatively charged functional groups, such as sulfonates. Such dyes are mostly employed in dyeing wool, silk, and nylon. They are highly soluble and exhibit electrostatic repulsion of negatively charged surfaces in natural surroundings, which makes them mobile in water bodies, making their elimination difficult [18], [19]. Reactive and vat dyes are compounds that react with textile fibers to create covalent bonds, providing a high level of color fastness and resistance to washing and light [20]. However, their good chemical stability makes it difficult to degrade and extract during wastewater treatment, allowing them to persist in industrial effluents. The dumping of wastewater containing dyes has devastating effects on the environment, as it limits the amount of light penetration and, consequently, photosynthesis in aquatic environments. Many dyes and their degradation products are toxic, mutagenic, cytotoxic, or carcinogenic, which presents a significant danger to human health through contaminated water sources, as discussed in Table II. Such concerns have resulted in strict regulations on the discharge of dyes, with a focus on effective treatment technologies.

TABLE II. MAJOR CLASSES OF INDUSTRIAL DYES AND THEIR ENVIRONMENTAL IMPLICATIONS

Dye Class	Charge Nature	Typical Industrial Applications	Environmental Persistence	Health & Ecological Risks	References
Azo dyes	Neutral / anionic	Textiles, leather, plastics	Highly recalcitrant	Carcinogenic aromatic amines	[21]
Cationic dyes	Positive	Acrylic fibers, paper	High	Acute toxicity to aquatic life	[16], [17]
Anionic dyes	Negative	Wool, silk, nylon	Moderate - high	Poor biodegradability	[18], [19]
Reactive dyes	Variable	Cotton textiles	Very high	Resistant to biological treatment	[20]
Vat dyes	Neutral	Denim and textiles	Extremely high	Long-term ecological damage	[22]

IV. CURRENT METHODOLOGIES FOR DYE REMOVAL FROM WASTEWATER

TABLE III. COMPARISON OF DYE REMOVAL TECHNOLOGIES WITH FOCUS ON ADSORPTION

Treatment Method	Removal Efficiency	Operational Complexity	Major Drawbacks	Suitability for Dye Effluents	References
Coagulation - flocculation	Moderate-high	Low	Sludge generation	Limited	[24]
Membrane filtration	Very high	High	Fouling, high cost	Selective	[25]
Advanced oxidation processes (AOPs)	High	Very high	Energy intensive	Effective but costly	[26]
Biological treatment	Low-moderate	Moderate	Poor for recalcitrant dyes	Limited	[25]
Adsorption (biochar)	High	Low	Optimization of adsorbent required	Highly suitable	[27]

Dye elimination techniques include physical, chemical, and biological methods. High removal efficiencies can be attained using physical methods, e.g. membrane filtration; however, high costs and fouling are limitations. Other approaches, such as chemical processes, coagulation-flocculation, and advanced oxidation processes, are effective, although they produce secondary sludge or consume a lot of energy and chemicals. Biological techniques are non-toxic to the environment, although they commonly face difficulties with persistent dyes [23]. Among them, adsorption has become a leading method because it is simple, effective, and flexible. Another alternative to commercially activated carbon is biochar-based adsorption especially when using biochar made from the cheap farming waste. Table III compares conventional dye removal technologies, their efficiencies, and the factors explaining why they are applicable to dye contaminated wastewater.

V. Mechanisms of Dye Adsorption on Biochar

Biochar produced from the waste of tender coconuts is promising in dye adsorption methods due to its porous structure, high carbon content, and variable surface chemistry. Cationic, anionic, and reactive dyes were investigated for their elimination under the influence of raw and activated biochar. Activation of the surfaces using acids (e.g. H_3PO_4 and HCl), bases (e.g. KOH and NaOH) or salts (e.g. $ZnCl_2$) leads to a huge expansion of the surface area, pore volume and density of functional groups, and thus better adsorption properties. The adsorption of dyes to biochar prepared from tender coconuts involves several mechanisms that interact with each other depending on the dye structure, solution chemistry, and biochar characteristics.

A. Electrostatic interactions.

Cationic dyes have a positive charge that strongly attracts negatively charged biochar surfaces, especially at pH values above the point of zero charge (pHpzc). On the other hand, the adsorption of anionic dyes is more favourable at lower pH values [16], [17].

B. π-π interactions

The π-π stacking interactions occurred due to the aromatic structures present in both dye molecules and biochar surfaces, especially for azo and reactive dyes [28].

C. Hydrogen bonding and Pore Filling

Hydrogen bonds between dye molecules and functional groups on char surfaces produce -OH, -COOH, and -NH_2 functional groups on biochar surfaces. Micropores and mesopores provide physical space for dye molecules, which would increase the adsorption capacity [29].

Behaviour synergy is frequently the result of these mechanisms acting in combination; therefore, synergistic adsorption behaviour is observed.[29].

VI. Advantages of using Tender Coconut Biochar as an Inexpensive Adsorbent

Coconut waste in the tender form was transformed into biochar, which detected dyes promisingly because of its porosity, high carbon structure, and tuneable surface chemistry. The actuation and crude biochar were investigated for the elimination of cationic, reactive, and anionic dyes. The surface area, pore volume and density of the functional groups are highly increased, and adsorption performance is enhanced through chemical activation of the surface by acids (e.g. H_3PO_4 and HCl) or bases (e.g. KOH and NaOH) or salts (e.g. $ZnCl_2$). The current interest in biochar as a wastewater treatment technique can be attributed to the fact that the technique is cheap, eco-friendly, and capable of operating as a strong adsorber. Compared to traditional adsorbents, including commercialized activated carbon, biochar using agricultural by-products, especially tender coconut waste, is advantageous for large-scale wastewater treatment systems. The main benefit of biochar is that it is inexpensive to produce [30]. Coconut waste is found in large quantities in tropical areas, and the tender coconuts are usually considered to be of little use.

Using this waste to generate biochar will lead to zero material costs and lower disposal costs. Biochar production requires only a small infrastructure, making it viable for small- to medium-scale use in developing nations. Biochar can also exhibit similar dye adsorption efficiencies at a significantly lower cost compared to commercial activated carbon, which requires high-temperature treatment and costly materials [31]. The transformation of tender coconut waste into biochar aligns with the principles of a circular economy. Transforming waste to biochar produces a useful product to remediate the environment as opposed to decomposing or incinerating waste which emits greenhouse gases. Adsorption using biochar produces a smaller quantity of second-generation waste than chemical treatment.

Biochar can be reused or repurposed to improve soil after use, or regenerated, and the management of contaminants. The pyrolysis temperature, heating rate, residence time, and the methods used for pyrolysis activation can be changed to adjust the physicochemical properties of biochar. Biochar made from tender coconut waste can be tailored to certain dye types: cationic dyes which are negatively charged by nature and contain oxygen-carrying functional groups; anionic dyes via surface or pH control; and aromatic dyes via π-π interactions. This flexibility can be customized to suit different industrial wastewater contents [32].

VII. Characteristics of Biochar Governing Dye Adsorption

The biochar surface area, pore structure, surface functional groups, surface charge, aromaticity, and stability are the main factors that affect the adsorption efficacy of biochar. A large surface area and good development of micropores are also significant contributors to the adsorption capacity, and surface functional groups are good facilitators of both electrostatic interactions and hydrogen bonding [32]. The π-π interactions of the dye molecules with the aromatic carbon domains are also involved, as shown in Figure 2. The thermal and chemical stability of tender coconut biochar is admirable; therefore, it can be used in repeated TDS adsorption-desorption cycles [33]. The relationship between key biochar features and the most dominant dye adsorption processes was examined. Table IV is organized systematically, showing how biochar produced from tender coconut waste can be streamlined to achieve the best results for many dye classes.

TABLE IV. Biochar Characteristics and Dominant Dye Adsorption Mechanisms

Biochar Property	Description	Dominant Adsorption Mechanism	Target Dye Types	References
High surface area	Developed via activation	Pore filling	Small molecular dyes	[34]
Microporous structure	<2 nm pores	Physical adsorption	Cationic dyes	[34]
Oxygenated functional groups	–OH, –COOH	Hydrogen bonding, electrostatic attraction	Cationic dyes	[34]
Aromatic carbon domains	Graphitic structure	π–π interactions	Azo, reactive dyes	[34]
pH-dependent surface charge	pHpzc controlled	Electrostatic interaction	Anionic / cationic dyes	[35]

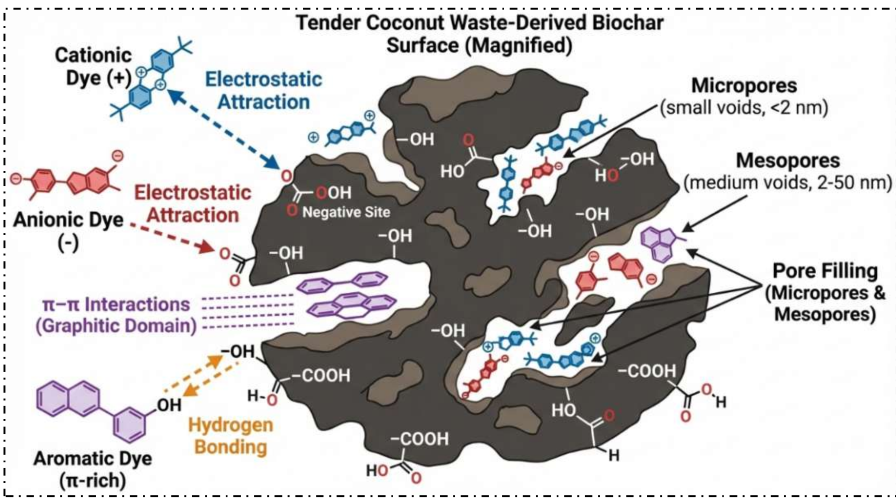

Figure 2. Schematic illustration of adsorption mechanisms in dye removal by tender coconut waste-derived biochar, including electrostatic interactions, π–π interactions, hydrogen bonding, and pore filling.

VIII. Economic Aspects of using Tender Coconut Waste Derived Biochar

Wastewater treatment technologies cannot be practiced on a large scale and over time without considering their economic viability. In this respect, biochar from tender coconut wastes offers a significant economic benefit over traditional adsorbents and treatment processes, especially in areas where the consumption and treatment of coconuts are high[27]. Table V provides a comparative study of the economic and sustainability of tender coconut biochar and commercial activated carbon. This evaluation indicates the enormous potential of biochar as a cheap and viable adsorbent in developing nations and locations with high coconut manufacture [36].In addition to the direct cost reduction, there are indirect socio-economic benefits of biochar obtained using tender coconuts waste. It enables the conversion of waste into useful resources, generates jobs at the local level, and assists in decentralized wastewater treatment plans [37]. Moreover, a decrease in open waste dumping and the ensuing pollution of the environment also leads to economic and health development in the long term [38]. Overall, the low price of raw materials, payment of moderate production costs, reusability, and other environmental advantages make biochar made from tender coconut waste an economically viable choice for dye extraction from industrial wastewater.

TABLE V. ECONOMIC AND SUSTAINABILITY COMPARISON OF TENDER COCONUT BIOCHAR AND ACTIVATED CARBON

Parameter	Tender Coconut Biochar	Commercial Activated Carbon	Economic Implication	References
Feedstock cost	Negligible	High	Reduced raw material cost	[38]
Production energy	Moderate	Very high	Lower operational cost	[39]
Regeneration feasibility	High	Moderate	Lower lifecycle cost	[39]
Environmental impact	Positive (waste valorization)	Neutral	Circular economy benefit	[39]
Suitability for developing regions	High	Limited	Scalable & affordable	[39]

IX. CONCLUSION

The release of effluents from industrial activities laden with dyes is a major environmental challenge because synthetic dyes are persistent and toxic. The traditional methods of wastewater treatment have been linked to high prices, secondary pollution, or low effectiveness with recalcitrant dyes. It has also come out to be a viable mode of treatment, especially when it is used alongside sustainable adsorbents in the name of adsorption. The review shows the potential of tender coconut waste as an adsorbent in the form of biochar to eliminate industrial dyes in aqueous systems. Tender coconut waste is a renewable and abundant source of biomass with a good composition for use in biochar. The biochar obtained thus far shows a high surface area, formed pore structure, plenty of surface functional groups, and structural integrity, which renders its applications in the dye adsorption process viable through electrostatic attraction, π-π interactions, and pore filling. The advantages of biochar produced from tender coconut waste are that it is cheap to produce, sustainable, regenerates itself, and follows the principles of a circular economy. The different classes of dyes can be easily removed owing to the conditions of the pyrolysis and activation processes. The use of tender coconut waste biochar is also a treatment and use of wastewater, particularly in coconut-producing areas. However, there is a need to standardize the production processes and to determine the performance over the long term, where industrial influences are involved. Lastly, biochar made from tender coconut waste can serve as an alternative biochar to eliminate industrial dyes because it is renewable and low-cost and can be expanded once successful experiments have been undertaken.

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