

RESEARCH ARTICLE

Valorization of Raw and Carbonized Cocos nucifera Coir as Low–Cost Adsorbents for the Removal of Cationic and Anionic Dyes from Aqueous Environments: A Comparative Investigation

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ABSTRACT: The discharge of synthetic dyes into water bodies from various industrial operations has emerged as a significant environmental concern owing to their persistent nature, toxicity, and potential carcinogenic effects. The present investigation undertakes a comparative evaluation of raw and carbonized Cocos nucifera coir for the adsorptive removal of crystal violet, brilliant green, and congo red from aqueous solutions. The carbonized adsorbent was prepared through thermal treatment of dried coconut coir powder at 600 °C for 30 minutes, followed by cooling to ambient temperature. Batch adsorption experiments were systematically conducted to evaluate the influence of critical operational parameters including initial dye concentration, contact time, and solution pH on the removal efficiency. The experimental findings revealed that carbonized coir exhibited markedly superior adsorption performance compared to the raw material across all three dye systems. Optimal adsorption was achieved at pH 6, with equilibrium established within 120 minutes of contact time. Maximum removal efficiencies of 95.60%, 95.28%, and 91.30% were recorded for crystal violet, brilliant green, and congo red respectively at an initial dye concentration of 20 mg/L. The enhanced adsorption capacity of the carbonized material is attributed to the development of porous structure and improved surface functionality during thermal treatment. The study demonstrates that carbonized Cocos nucifera coir represents an economically viable, environmentally benign, and highly effective adsorbent for the remediation of dye-contaminated wastewater, offering the distinct advantage of generating no secondary pollution.

Keywords: Adsorption, Cocos nucifera coir, Crystal violet, Brilliant green, Congo red, Carbonization, Wastewater treatment

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1. INTRODUCTION

Over the past few decades, the escalating contamination of freshwater resources has emerged as one of the most pressing environmental challenges worldwide. Rapid industrialization,

coupled with inadequate wastewater treatment infrastructure, has led to the widespread discharge of toxic pollutants into rivers, lakes, and groundwater reserves. Among the myriad of contaminants, synthetic dyes constitute a particularly problematic class of organic pollutants owing to their intense coloration, high chemical stability, and resistance to natural degradation pathways, as extensively documented in the literature [1]. These dyes are extensively employed in textiles, paper manufacturing, leather tanning, food processing, pharmaceuticals, and cosmetics, and their effluents are often released into water bodies without adequate pretreatment [2]. The presence of even minute concentrations of dyes in water

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is aesthetically unpleasant and, more critically, impedes light penetration, thereby disrupting photosynthetic activity in aquatic plants and disturbing the entire food chain. Furthermore, many synthetic dyes and their metabolic by-products exhibit mutagenic, carcinogenic, and teratogenic properties, posing direct health risks to humans and aquatic organisms [3]. Consequently, the removal of such dyes from industrial wastewater before discharge has become an environmental imperative.

A variety of conventional treatment technologies have been explored for dye remediation, including photocatalysis, membrane filtration, ozonation, electrochemical oxidation, coagulation-flocculation, and adsorption [4]. Among these, adsorption has gained widespread acceptance due to its operational simplicity, high removal efficiency, insensitivity to toxic substances, and economic feasibility. The process does not introduce secondary pollutants and can be designed to treat large volumes of water with relatively low energy input. The performance of adsorption, however, is critically dependent on the nature of the adsorbent material. Activated carbon has long been the benchmark adsorbent because of its large surface area, well-developed porosity, and favorable surface chemistry. Nevertheless, the commercial production of activated carbon from non-renewable precursors such as coal or petroleum coke is energy-intensive and expensive, limiting its large-scale application in developing countries [5]. This economic constraint has driven researchers to search for alternative, low-cost adsorbents derived from agricultural and industrial by-products [6].

Agricultural wastes, which are generated in enormous quantities globally, represent an untapped reservoir of carbon-rich materials suitable for adsorbent synthesis. Their utilization not only offers a sustainable waste management strategy but also provides a cost-effective route for water purification [14]. Among the various lignocellulosic residues, coconut (*Cocos nucifera*) coir has attracted considerable attention. Coconut is cultivated extensively in tropical regions, with global production exceeding 54 billion nuts per annum; India alone contributes approximately 13 billion nuts annually. The fruit shell and the fibrous coir, which constitute about 35 % of the fruit mass, are generally discarded as solid waste, creating disposal challenges. Recognizing this, several studies have investigated the adsorptive potential of coconut-based materials, including coir dust, coconut bunch waste, and activated carbon derived from coconut shells [7, 8]. These studies have demonstrated that coconut-derived adsorbents possess appreciable affinity for various dyes and heavy metals, largely due to their fibrous structure, surface functional groups, and moderate porosity. The success of these agricultural residues has also inspired investigations into other biomass sources, such as rambutan peel, sugarcane bagasse, and date seeds, which have shown promising results for dye sequestration [9, 11, 16].

However, a critical gap remains in the systematic comparison between raw, unmodified coir and its carbonized counterpart for the simultaneous removal of both cationic and anionic dyes. Raw coir contains abundant hydroxyl, carboxyl, and phenolic groups that can participate in

electrostatic and hydrogen-bonding interactions, whereas carbonization at elevated temperatures (typically 600-900 °C) transforms the lignocellulosic matrix into a more graphitic, porous structure with enhanced specific surface area and altered surface charge characteristics. The trade-off between retaining native functional groups and developing porosity has not been thoroughly examined for a range of dye types. Moreover, most previous works have focused on single-dye systems, whereas industrial effluents often contain mixtures of dyes with different ionic natures. While advanced composite materials, including magnetic nanoparticles, carbon nanotubes, and core-shell microspheres, have demonstrated remarkable adsorption capacities, their synthesis often involves multiple steps, toxic reagents, and high energy consumption, which limit their practical applicability in resource-constrained settings [10,12,13,15,17-19]. A comprehensive evaluation of the adsorption behavior of both raw and carbonized coir towards structurally diverse dyes, such as the cationic triphenylmethane dyes crystal violet and brilliant green, and the anionic diazo dye congo red, would provide valuable insights into the underlying adsorption mechanisms and guide the selection of the most suitable form for specific wastewater treatment scenarios.

The novelty of the present work lies precisely in this comparative approach. We systematically investigate and contrast the adsorption performance of raw *Cocos nucifera* coir and its carbonized derivative for the removal of three representative dyes that differ in their molecular size, charge, and functional groups. Beyond simply reporting removal percentages, we examine the influence of key operational parameters, initial dye concentration, contact time, and solution pH, on the adsorption efficiency for each dye-adsorbent system. This multifaceted comparison enables us to identify the optimal conditions for each dye and to rationalize the observed differences in terms of surface chemistry and textural properties. Furthermore, by demonstrating that carbonized coir, despite its lower functional group density, outperforms the raw material in dye uptake, we highlight the dominant role of pore structure and π - π interactions over simple electrostatic attraction for these particular dyes. The study also emphasizes the economic and environmental benefits of using waste coconut coir as a precursor, since the carbonization process is straightforward, requires no chemical activation agents, and yields a product that can be readily separated and reused. Such an approach aligns with the growing interest in green and sustainable materials, which have also found applications beyond water treatment, including in active packaging and other industrial sectors [20]. Our findings contribute to the growing body of knowledge on the valorization of agricultural residues and offer a practical, low-cost solution for dye-laden wastewater treatment that aligns with the principles of green chemistry and circular economy.

In this paper, we report the preparation of carbonized adsorbent from coconut coir and its comparative evaluation against the raw material for the adsorption of crystal violet, brilliant green, and congo red from aqueous solutions. The

effects of initial dye concentration, contact time, and pH are systematically studied, and the equilibrium adsorption data are interpreted in the context of surface properties and dye characteristics. The results demonstrate that carbonized coir is a highly effective, economical, and eco-friendly adsorbent that does not generate secondary pollution, thus offering a promising alternative to commercial activated carbons for the remediation of dye-contaminated wastewater.

2. EXPERIMENTAL DETAILS

2.1. Adsorbate

The dyes selected for this investigation, namely crystal violet (CV), brilliant green (BG), and congo red (CR), were procured from CDH Limited, India, and were of analytical reagent grade. These dyes were employed without further purification. A stock solution of each dye was prepared by accurately weighing 1 gram of the respective dye and dissolving it in 1 liter of double distilled water to obtain a concentration of 1000 mg/L. The stock solutions were stored in amber glass bottles to prevent photodegradation and were kept under refrigeration when not in use. Working solutions of varying initial concentrations (20 to 100 mg/L) were subsequently prepared by appropriate dilution of the stock solutions with double distilled water immediately prior to each adsorption experiment to ensure solution stability and to avoid any ageing effects.

2.2. Synthesis of Adsorbent

The precursor material utilized in the present study was coconut coir, which was collected as agricultural waste from local coconut processing units. The collected coir was thoroughly washed with tap water to remove adhering dust and other extraneous impurities, followed by repeated rinsing with distilled water to eliminate any soluble contaminants. The washed coir was then subjected to sun drying for 48 hours, after which it was placed in a hot air oven maintained at 100 °C for approximately 24 hours until constant mass was achieved, indicating complete removal of moisture content. The dried coir was subsequently pulverized using a mechanical grinder and the resulting powder was sieved through a 250 µm mesh screen to obtain a uniform particle size fraction suitable for adsorption studies. For the preparation of carbonized adsorbent, 200 grams of the dried and sieved coir powder was transferred into a silica crucible and placed in a muffle furnace. The carbonization process was conducted at a temperature of 600 °C under self-generated atmosphere for a duration of 30 minutes. Upon completion of the heating cycle, the furnace was allowed to cool naturally to ambient temperature, and the resulting carbonized material was recovered, ground gently to break any agglomerates, and stored in an airtight desiccator for subsequent use in batch adsorption experiments.

2.3. Batch Adsorption Studies

Batch adsorption experiments were conducted to evaluate the dye removal efficiency of the prepared adsorbents and to investigate the influence of various operational parameters. In a typical adsorption run, 0.02 grams of the adsorbent (either raw or carbonized coir) was accurately weighed and introduced into a 250 mL Erlenmeyer flask containing 50 mL of dye solution of predetermined initial concentration. The flasks were then agitated in a temperature-controlled orbital shaking incubator maintained at 30 ± 2 °C, with a constant shaking speed of 200 rpm to ensure adequate mixing and to minimize external mass transfer resistance. The initial concentration of dyes was varied in the range of 20 to 100 mg/L to study the effect of this parameter on adsorption capacity. The contact time was systematically varied from 5 to 360 minutes to determine the time required to reach equilibrium. The solution pH was adjusted over a range of 4 to 10 using 0.1 M hydrochloric acid or 0.1 M sodium hydroxide solutions, and the pH values were measured using a calibrated digital pH meter to investigate the influence of this factor on the adsorption process.

Upon completion of the prescribed contact time, the flasks were removed from the shaker and the adsorbent was separated from the solution by centrifugation at 4000 rpm for 10 minutes. The residual dye concentration in the clear supernatant was determined using a UV-visible spectrophotometer (Elico, Model SL-164) at the characteristic wavelength of maximum absorbance (λ_{max}) for each dye. The λ_{max} values were found to be 588 nm, 625 nm, and 497 nm for crystal violet, brilliant green, and congo red, respectively. Calibration curves were constructed for each dye using standard solutions of known concentrations, and the molar absorptivity (slope) values were determined as 0.045, 0.0638, and 0.047 L/mg·cm for CV, BG, and CR, respectively. The percentage removal of dye was calculated using the following relationship:

$$\% \text{ Adsorption} = [(C_0 - C_e) / C_0] \times 100 \quad (1)$$

where C_0 represents the initial dye concentration (mg/L) and C_e denotes the equilibrium dye concentration (mg/L) remaining in the solution after adsorption. All experiments were performed in triplicate to ensure reproducibility, and the average values are reported with standard deviations not exceeding ± 2.0 %. The blanks and control experiments were run simultaneously under identical conditions to account for any possible dye loss due to photodegradation or adsorption onto the glassware surfaces.

3. RESULTS AND DISCUSSION

3.1. Comparative Adsorption Studies on Raw and Carbonized Coir

The comparative adsorption performance of raw and carbonized *Cocos nucifera* coir (CNC) towards crystal violet

(CV), brilliant green (BG), and congo red (CR) was evaluated under identical experimental conditions, and the results are presented in Figure 1. The investigation revealed that carbonized CNC consistently exhibited superior dye removal efficiency compared to its raw counterpart across all three dye systems. Specifically, for crystal violet, the carbonized adsorbent demonstrated a remarkable removal of 99 %, whereas the raw material achieved only 82 % under similar conditions. In the case of brilliant green, the adsorption efficiency was recorded as 93 % for carbonized CNC and 75 % for the raw coir. Similarly, congo red showed the lowest affinity among the three dyes, with carbonized CNC removing 91 % of the dye as opposed to only 71 % achieved by the raw material.

The enhanced performance of the carbonized adsorbent can be attributed to several physicochemical transformations that occur during the thermal treatment process. Carbonization at 600 °C induces the decomposition of the lignocellulosic matrix, resulting in the evolution of volatile components and the subsequent development of a highly porous structure with significantly increased specific surface area. This structural modification provides a greater number

of accessible adsorption sites for dye molecules [1]. Additionally, the carbonization process promotes the formation of graphitic domains and aromatic ring structures, which facilitate π - π stacking interactions between the adsorbent surface and the aromatic dye molecules, thereby enhancing the overall adsorption capacity [5,10]. The raw coir, while possessing native functional groups such as hydroxyl and carboxyl moieties capable of hydrogen bonding and electrostatic interactions, suffers from limited surface area and restricted pore accessibility, which collectively diminish its adsorption potential. Tharayil et al. [21] demonstrated the efficient adsorption of crystal violet using coir pith-derived biochar, confirming that carbonization significantly enhances the dye removal capacity of coconut-based materials. Similarly, a recent study on coconut husk biochar reported over 98 % removal of crystal violet, attributing the enhanced performance to the development of porous structure and improved surface functionality during thermal treatment [22]. Furthermore, the carbonized material exhibits improved mechanical stability and chemical resistance, making it more suitable for repeated use in wastewater treatment applications [7].

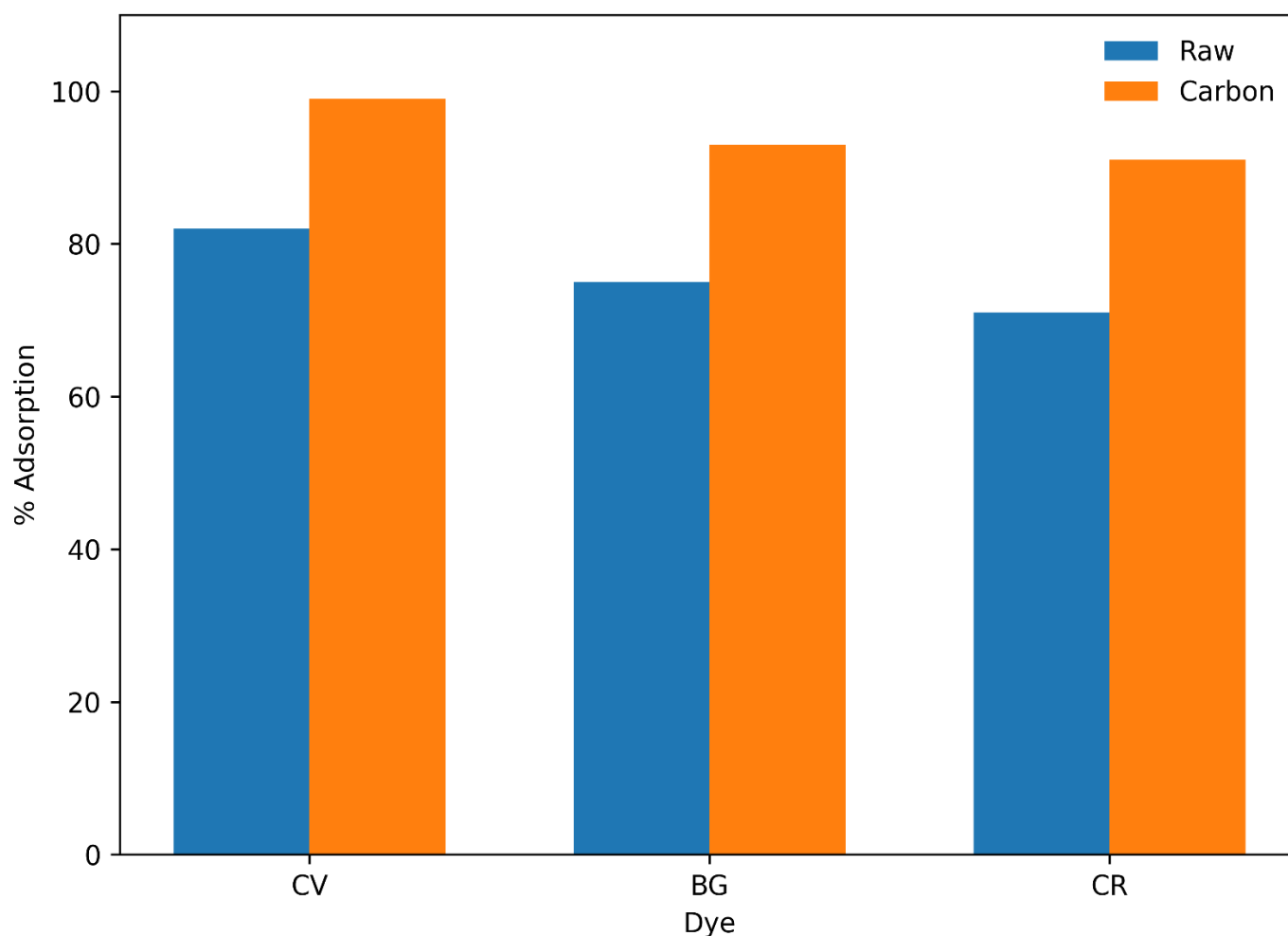


Fig. 1. Comparative adsorption of crystal violet (CV), brilliant green (BG), and congo red (CR) onto raw and carbonized *Cocos nucifera* coir (CNC). Experimental conditions: initial dye concentration 20 mg/L, adsorbent dosage 0.02 g, contact time 180 min, pH 6, temperature 303 K, agitation speed 200 rpm.

The mechanistic aspects of dye adsorption onto carbonized biomass, including the roles of π - π stacking interactions and hydrogen bonding, have been comprehensively elucidated by Gaya and Mohammed [23], who investigated coconut shell-derived activated charcoal for both cationic and anionic dye removal. The results clearly demonstrate that carbonization is a highly effective strategy for valorizing agricultural waste into a superior adsorbent material, and consequently, all subsequent investigations in this study were conducted exclusively with the carbonized CNC adsorbent.

3.2. Effect of Initial Dye Concentration

The influence of initial dye concentration on the adsorption process was systematically investigated by varying the dye concentration from 20 to 100 mg/L while maintaining constant conditions of contact time (240 min), pH (6.0), temperature (303 K), and adsorbent dosage (0.02 g). The results are depicted in Figure 2, which reveals a clear trend of decreasing percentage removal with increasing initial dye concentration for all three dyes under examination.

At the lowest initial concentration of 20 mg/L, the maximum percentage removals were observed, with values of 95.60 % for crystal violet, 95.28 % for brilliant green, and 91.30 % for congo red. However, as the initial concentration was progressively increased to 100 mg/L, the percentage removal values declined significantly to 73.7 %, 71.4 %, and

70.6 % for CV, BG, and CR, respectively. This inverse relationship between initial concentration and percentage removal can be rationalized by considering the availability of adsorption sites on the adsorbent surface. At lower initial concentrations, the ratio of available active sites to dye molecules is relatively high, allowing for near-complete removal of the adsorbate. The abundant vacant sites on the carbonized CNC surface readily accommodate the dye molecules through various binding interactions [11,14].

Conversely, at higher initial concentrations, the number of dye molecules in the bulk solution far exceeds the available adsorption sites on the adsorbent surface. Consequently, the active sites become rapidly saturated, leaving a substantial fraction of the dye molecules unadsorbed in the solution [12]. This saturation effect is particularly pronounced for congo red, which exhibited the lowest percentage removal among the three dyes, presumably due to its larger molecular size and anionic nature, which may impose steric hindrance and electrostatic repulsion with the negatively charged adsorbent surface at neutral pH. It is noteworthy that although the percentage removal decreased at higher concentrations, the actual adsorption capacity (mg of dye per gram of adsorbent) increased with increasing initial concentration, as the concentration gradient provides a greater driving force for mass transfer from the bulk solution to the adsorbent surface [13].

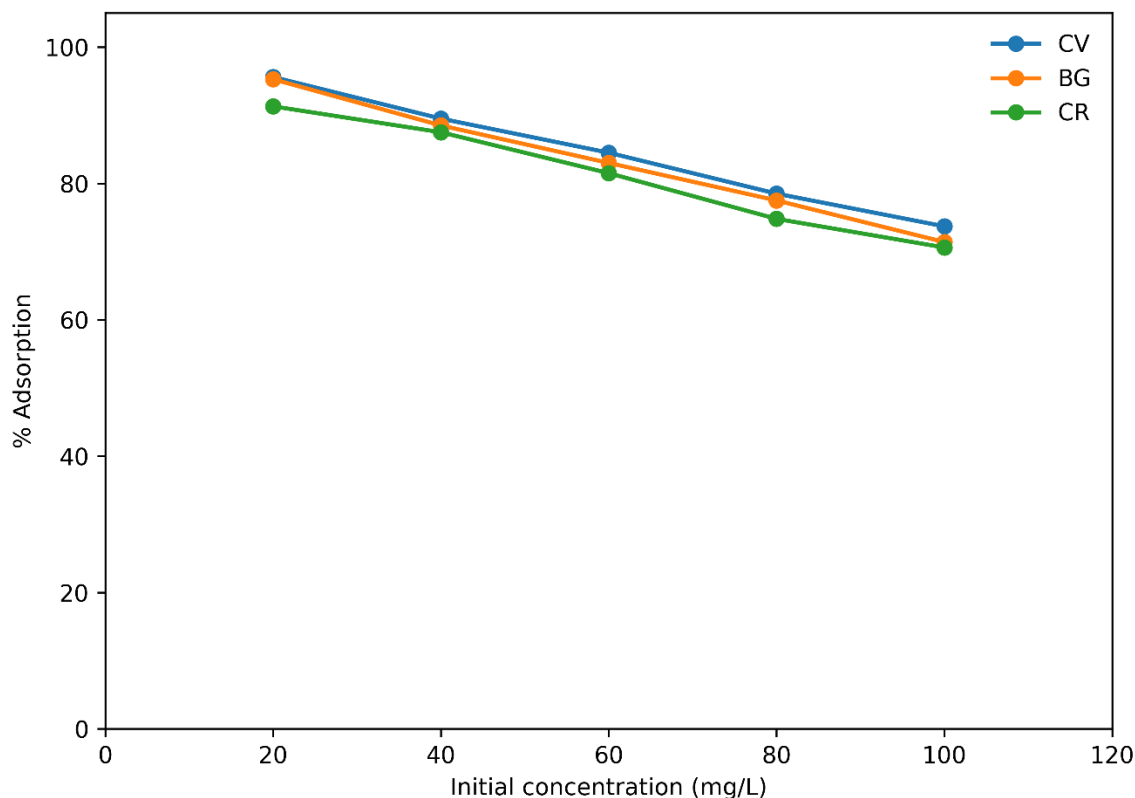


Fig. 2. Effect of initial dye concentration on the adsorption of crystal violet (CV), brilliant green (BG), and congo red (CR) onto carbonized *Cocos nucifera* coir. Experimental conditions: adsorbent dosage 0.02 g, contact time 240 min, pH 6, temperature 303 K, agitation speed 200 rpm.

This observation is consistent with the general principles of adsorption thermodynamics and has been widely reported in the literature for various adsorbent-adsorbate systems [17,24]. Eletta et al. [24] systematically studied the adsorption of congo red onto coconut shell-based activated carbon and reported that adsorption capacity increased with higher initial concentrations due to enhanced mass transfer driving force, although the percentage removal decreased at higher concentrations because of site saturation. This behavior was also observed by Gaya and Mohammed [23], who noted that the adsorption capacity (q_e) increased with higher initial concentrations owing to the enhanced mass transfer driving force, while the percentage removal decreased due to site saturation. Based on these findings, an initial dye concentration of 20 mg/L was selected for subsequent experiments to ensure optimal removal efficiency and to facilitate meaningful comparative analysis.

3.3. Effect of Contact Time and Adsorption Kinetics

The influence of contact time on the adsorption of the three dyes onto carbonized CNC was investigated over a time interval ranging from 5 to 360 minutes, and the results are presented in Figure 3. The experiments were conducted at an initial dye concentration of 20 mg/L, adsorbent dosage of 0.02 g, pH 6.0, and temperature of 303 ± 2 K.

The adsorption profiles revealed a biphasic kinetic behavior for all three dyes. An initial rapid adsorption phase

was observed during the first 60 minutes, during which the percentage removal increased sharply from 90.25 % to 97.8 % for crystal violet, from 89.05 % to 92.1 % for brilliant green, and from 69.4 % to 73.6 % for congo red. This initial fast uptake can be attributed to the abundance of readily accessible adsorption sites on the external surface of the carbonized adsorbent, where dye molecules encounter minimal diffusional resistance [22]. The availability of these vacant sites at the commencement of the adsorption process facilitates rapid binding through both physical and chemical interactions, including electrostatic attraction, hydrogen bonding, and π - π stacking.

Following the rapid initial phase, the adsorption rate gradually diminished, and equilibrium was attained at approximately 180 minutes for all three dyes. At equilibrium, the percentage removal values reached 99.45 % for crystal violet, 93.05 % for brilliant green, and 75.4 % for congo red. The progressive deceleration in adsorption rate with increasing contact time can be explained by the gradual occupation and saturation of the available surface sites. As the adsorption progresses, the remaining vacant sites become increasingly less accessible, either because they are located within the interior pore structure requiring diffusion through tortuous micropores or because the adsorbed dye molecules exert steric and electrostatic repulsion on the incoming adsorbate species [12]. The establishment of equilibrium indicates that the rate of adsorption equals the rate of desorption, and the adsorbent surface has reached its maximum capacity under the given experimental conditions.

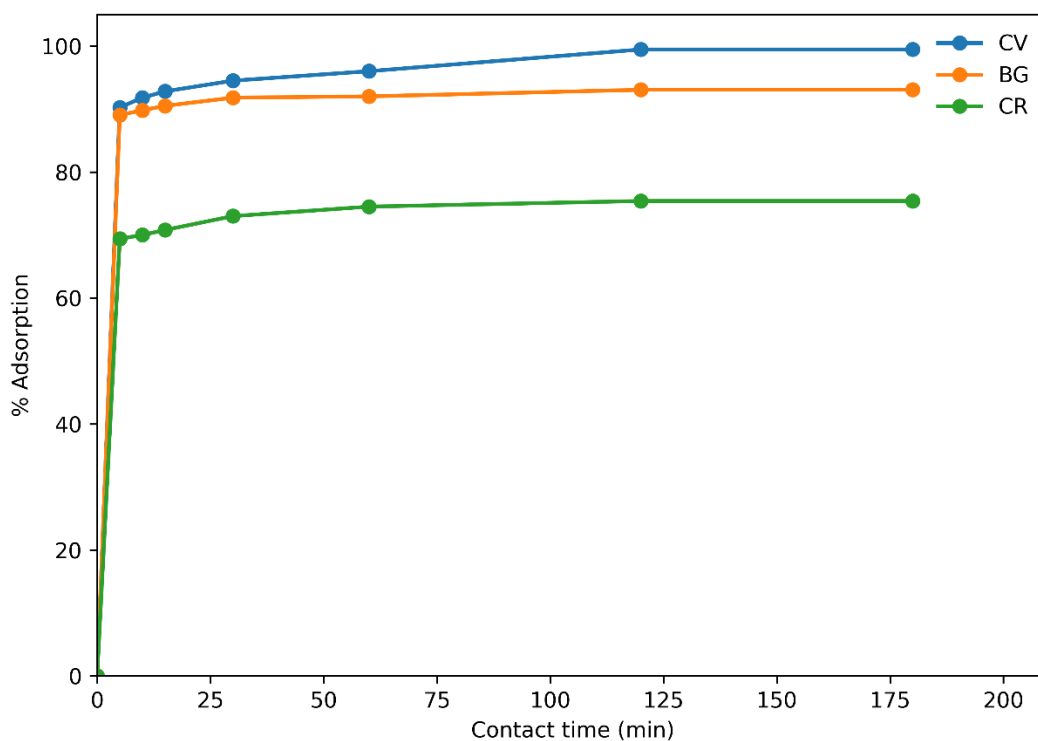


Fig. 3. Effect of contact time on the adsorption of crystal violet (CV), brilliant green (BG), and congo red (CR) onto carbonized *Cocos nucifera* coir. Experimental conditions: initial dye concentration 20 mg/L, adsorbent dosage 0.02 g, pH 6, temperature 303 K, agitation speed 200 rpm.

The biphasic kinetic behavior observed in our study is consistent with numerous reports on dye adsorption onto carbonaceous materials. The rapid initial uptake is attributed to the abundance of readily accessible adsorption sites on the external surface, while the subsequent slower phase reflects intra-particle diffusion into the internal pore structure [13,25]. Studies on biochar prepared at elevated pyrolysis temperatures have shown that adsorption kinetics are well described by the pseudo-second-order model, and that intraparticle diffusion plays a significant role in the overall adsorption process [13]. The equilibrium time of approximately 180 minutes observed in this study compared to some other agricultural adsorbents is a notable advantage, as it implies lower energy consumption and faster processing times in practical wastewater treatment applications. The complete adsorption profiles suggest that the carbonized CNC possesses a heterogeneous surface with both readily accessible external sites and less accessible internal sites, consistent with the porous nature of the material developed during the carbonization process [15,18]. This equilibrium time is comparable to that reported for coconut shell-based activated carbon for congo red removal, where equilibrium was attained at 180 minutes [24]. Based on these kinetic observations, a contact time of 180 minutes was adopted as the equilibrium time for all subsequent experiments.

3.4. Effect of Solution pH

The solution pH is a critically important parameter in the adsorption of ionic dyes, as it influences both the surface charge characteristics of the adsorbent and the ionization

state of the dye molecules in solution. The effect of initial pH on the adsorption of CV, BG, and CR onto carbonized CNC was examined over a pH range of 4.0 to 10.0, while maintaining constant conditions of initial concentration (20 mg/L), contact time (180 min), adsorbent dosage (0.02 g), and temperature (303 K). The results are graphically presented in Figure 4.

The experimental data revealed that maximum adsorption for all three dyes occurred at pH 6.0, with percentage removals of 98.33 % for crystal violet, 92.48 % for brilliant green, and 81.48 % for congo red. A further increase or decrease in pH resulted in a gradual decline in adsorption efficiency. The observed pH-dependent adsorption behavior can be comprehensively explained by considering the surface chemistry of the carbonized CNC and the nature of the dye species.

At lower pH values ($\text{pH} < 6$), the aqueous solution contains a higher concentration of hydronium ions (H_3O^+), which can protonate the surface functional groups present on the carbonized adsorbent, such as hydroxyl, carboxyl, and phenolic moieties. This protonation imparts a net positive charge to the adsorbent surface, thereby creating a favorable electrostatic environment for the adsorption of anionic dyes such as congo red through electrostatic attraction [16]. The concept of pH_{pzc} (point of zero charge) is crucial for understanding these interactions, as the adsorbent surface becomes positively charged below the pH_{pzc} and negatively charged above it [26]. For anionic dyes such as congo red, adsorption is favoured under acidic conditions ($\text{pH} 4\text{--}6$) where protonation of surface functional groups creates a positively charged surface that attracts the negatively charged dye molecules [23].

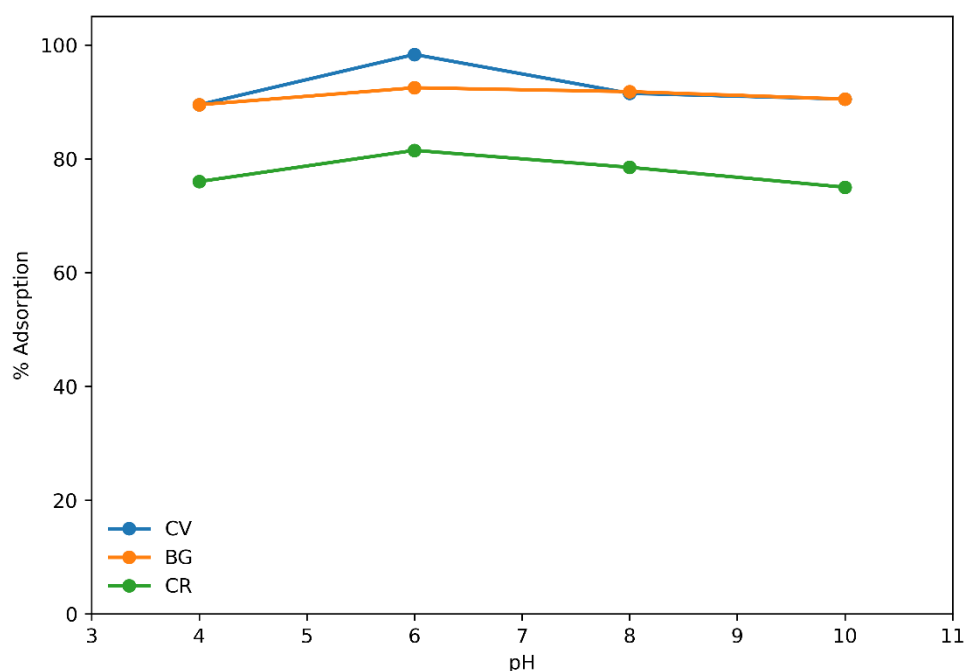


Fig. 4. Effect of initial solution pH on the adsorption of crystal violet (CV), brilliant green (BG), and congo red (CR) onto carbonized *Cocos nucifera* coir. Experimental conditions: initial dye concentration 20 mg/L, adsorbent dosage 0.02 g, contact time 180 min, temperature 303 K, agitation speed 200 rpm.

However, in the present study, the maximum adsorption for CR was also observed at pH 6, which suggests that electrostatic interactions alone do not govern the overall adsorption process for this anionic dye. The relatively lower removal of CR compared to the cationic dyes (CV and BG) can be attributed to the anionic nature of the dye and the presence of negative surface charges on the adsorbent at neutral to alkaline pH, leading to electrostatic repulsion [13,14]. Additionally, the molecular structure of congo red, which contains two azo groups and multiple sulfonic acid moieties, results in a larger molecular dimension compared to the cationic dyes, potentially causing diffusional limitations and steric hindrance during adsorption [11].

For the cationic dyes crystal violet and brilliant green, the adsorption behavior exhibits a different trend. At pH values below the point of zero charge of the adsorbent, the surface is positively charged, which would be expected to repel the positively charged cationic dye molecules. However, the experimental results show high adsorption even at lower pH, indicating that other mechanisms, such as hydrogen bonding, π - π interactions, and hydrophobic interactions, play a predominant role in the adsorption of these dyes [9,19]. Conversely, for cationic dyes such as crystal violet and brilliant green, adsorption is generally favored under alkaline conditions where the deprotonated surface attracts the positively charged dye species [27]. The reduction in adsorption observed at higher pH values (pH > 6) can be attributed to the deprotonation of surface functional groups, resulting in a negatively charged adsorbent surface that repels the cationic dye molecules. Furthermore, at elevated pH, the hydroxyl ions in the solution may compete with the dye molecules for the available adsorption sites, thereby reducing the overall removal efficiency [20].

The observation that pH 6.0 represents the optimal condition for all three dyes, despite their differing ionic characters, indicates that the carbonized CNC surface possesses a heterogeneous distribution of functional groups capable of interacting with both cationic and anionic species through a combination of electrostatic and non-electrostatic mechanisms. This multi-mechanism adsorption process, involving electrostatic interactions, hydrogen bonding, π - π stacking, and pore diffusion, has been confirmed by comprehensive characterization studies on coconut shell-derived adsorbents [23]. The greater adsorption of cationic dyes compared to anionic dyes by biochars has been attributed to their smaller molecular weight, favorable electrostatic properties, and stronger π - π interactions with the biochar surface [13]. This versatility is a desirable attribute for an adsorbent intended for treating complex industrial effluents that may contain mixtures of different dye types. The pH studies thus confirm that the carbonized coir is a robust and adaptable adsorbent, and pH 6.0 was selected as the optimum for all subsequent adsorption studies.

The comprehensive results and discussion presented in this section collectively demonstrate that carbonized *Cocos nucifera* coir is a highly effective and versatile adsorbent for the removal of both cationic and anionic dyes from aqueous solutions. The superior performance of the carbonized

material over its raw counterpart, coupled with the systematic optimization of key operational parameters, establishes this agricultural waste-derived adsorbent as a promising, sustainable, and cost-effective alternative to conventional commercial adsorbents for wastewater treatment applications. The findings contribute to the growing body of knowledge on the valorization of agricultural residues and offer a practical solution for dye-laden wastewater remediation that aligns with the principles of green chemistry and circular economy.

4. CONCLUSIONS

The present investigation successfully demonstrates the potential of waste coconut coir as an effective and sustainable adsorbent for the removal of hazardous synthetic dyes from aqueous solutions. Through systematic comparative analysis, it has been established that carbonized *Cocos nucifera* coir exhibits markedly superior adsorption performance compared to its raw counterpart for crystal violet, brilliant green, and congo red. The enhanced removal efficiency of the carbonized material is attributed to the development of a porous structure, increased specific surface area, and the formation of graphitic domains during thermal treatment at 600 °C, which collectively facilitate multiple adsorption mechanisms including electrostatic interactions, hydrogen bonding, and π - π stacking. The optimization of key operational parameters revealed that maximum adsorption for all three dyes occurred at pH 6.0, with equilibrium being attained within 180 minutes of contact time. The initial dye concentration studies demonstrated that while percentage removal decreased at higher concentrations, the actual adsorption capacity increased due to enhanced mass transfer driving force. The findings validate that adsorption technology remains one of the most efficient, simple, and cost-effective approaches for dye decolorization from wastewater. The carbonized CNC adsorbent offers several compelling advantages including economic viability, environmental benignity, and the absence of secondary pollution generation. Furthermore, the utilization of agricultural waste material for adsorbent production aligns with the principles of circular economy and green chemistry, providing a dual benefit of waste management and water remediation. Based on the comprehensive results obtained, carbonized *Cocos nucifera* coir can be recommended as a promising, low-cost, and eco-friendly alternative to commercial activated carbons for the effective treatment of dye-contaminated industrial effluents.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or

conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

Availability of data and material

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

All authors contributed equally to this work.

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