IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, October 2026
Impact Factor: 8.2

Dye Removal from Aqueous Wastewater Using KOH-Treated Areca Nut-Based Activated Carbon: Characterization, Adsorption Mechanism, and Optimization—A Comprehensive Review

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Abstract: *Bismarck Brown is a synthetic azo dye used in textile processing, paper production, leather processing, and biological staining. Its discharge in wastewater is a concern because many azo dyes are chemically stable, resist natural degradation, and reduce light penetration in receiving waters. Adsorption is an attractive treatment option because it is comparatively simple to operate, effective for dissolved pollutants, and compatible with low-cost waste-derived adsorbents. Processing of areca nut (Areca catechu L.) generates large quantities of husk, pod, shell, and fibre, whose lignocellulosic composition makes them suitable precursors for biosorbents, biochar, and activated carbon. This review examines the potential of KOH-treated areca-nut-derived activated carbon for removing Bismarck Brown from aqueous wastewater. Because the direct literature is limited, studies of areca-based adsorbents for other dyes (Brilliant Green, Methylene Blue, Methyl Orange, Rhodamine B, and Alizarin Red S) and of Bismarck Brown adsorption on other materials are used as supporting evidence. The reviewed areca-based adsorbents report capacities of approximately 18.21 to 785.3 mg/g, the highest value being for Methylene Blue on magnetic biochar from areca nut husk, whereas only one directly relevant study (Bismarck Brown-Y on areca husk carbon fibre) was identified, indicating a clear research gap. Possible adsorption mechanisms (electrostatic attraction, hydrogen bonding, π–π interactions, pore filling, surface complexation, and van der Waals forces), characterization strategies (FTIR, SEM–EDX, XRD, BET, and pH_{pzc}), and a systematic experimental framework covering operating variables, equilibrium, kinetics, thermodynamics, and regeneration are discussed. The review concludes that areca-derived activated carbon is a promising but insufficiently studied adsorbent for Bismarck Brown, and that its performance and mechanism must be established experimentally*

Keywords: Areca nut, *Areca catechu*, Bismarck Brown, dye removal, adsorption, biosorbent, biochar, activated carbon, KOH activation, agricultural waste, wastewater treatment, FTIR, SEM–EDX, XRD, BET, adsorption kinetics, adsorption isotherms.

I. INTRODUCTION

The expansion of industries such as textiles, paper, leather, pharmaceuticals, printing, and related manufacturing has increased the generation of wastewater containing numerous organic pollutants. Synthetic dyes are particularly important contaminants because they are deliberately designed to provide strong colour and chemical stability. Even

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small quantities of dye can cause visible colouration in water, reduce light penetration, and potentially interfere with photosynthetic activity in aquatic systems.

Synthetic dyes can be divided into several groups according to their chemical structure and industrial use, including azo, anthraquinone, triphenylmethane, and xanthene dyes. Azo dyes are among the most widely used synthetic dyes and contain one or more azo linkages (–N=N–) connecting aromatic structures. Their chemical stability makes them useful industrially but can also make their removal from wastewater difficult.

Bismarck Brown is a synthetic azo dye also known as Bismarck Brown R, Bismarck Brown Y, Bismarck Brown G, Vesuvine, and C.I. Basic Brown 1. It has been used in textile, paper, leather, and biological-staining applications, and its presence in wastewater therefore requires suitable treatment before discharge [1–8].

Different technologies have been investigated for dye removal, including coagulation–flocculation, membrane filtration, oxidation, photocatalytic treatment, biological processes, electrochemical treatment, and adsorption. The suitability of a method depends on factors such as dye concentration, chemical structure, treatment cost, energy requirements, and operating conditions. Among these methods, adsorption has received considerable attention because it can provide effective pollutant removal with relatively simple equipment. Activated carbon is one of the most widely used adsorbents because of its developed pore structure, high surface area, and ability to interact with a variety of pollutants; however, the preparation, purchase, and regeneration of high-quality commercial activated carbon can increase treatment costs.

For this reason, agricultural residues have increasingly been investigated as alternative adsorbent precursors. They are renewable and frequently rich in cellulose, hemicellulose, lignin, and oxygen-containing functional groups, and can be used directly as biosorbents or transformed into biochar, activated carbon, carbon fibres, carbon nanospheres, and composite adsorbents [9–17]. Such conversion reduces the quantity of agricultural waste requiring disposal and yields a potentially useful material for wastewater treatment, thereby supporting waste valorisation and the principles of a circular economy.

Areca nut (*Areca catechu* L.) is a particularly interesting agricultural residue for this purpose. Its processing generates husk, shell, pod, and fibre wastes that contain lignocellulosic components and surface groups capable of interacting with dissolved pollutants [12, 16, 18, 19]. Areca nut need not be used only as untreated biomass: alkali treatment can modify the lignocellulosic structure and expose additional adsorption sites, pyrolysis can convert biomass into a carbon-rich material, activation can increase pore development and accessible surface area, and magnetic modification can simplify separation of the adsorbent after treatment [9, 10, 15–17].

Previous studies have demonstrated the potential of areca-nut-derived materials for removing different pollutants. Chemically modified areca-nut husk has been investigated for Brilliant Green removal, while carbonised and activated areca materials have been investigated for Methylene Blue and other dyes [9–11, 15–17]. Areca-based materials have also been studied for heavy metals and pharmaceutical contaminants [12, 14].

Bismarck Brown has been studied using several adsorbents other than areca nut, including activated carbons, agricultural wastes, sewage sludge, mesoporous silica, carbon nanotubes, graphene-based materials, chitosan composites, and inorganic materials [1–8, 20–24]. These studies provide useful information about adsorption equilibrium, kinetics, thermodynamics, and possible interactions between Bismarck Brown and adsorbent surfaces. The possible mechanisms include electrostatic attraction, hydrogen bonding, π–π interactions, pore filling, surface complexation, and van der Waals forces, and their relative importance depends on the chemical properties of the dye and adsorbent and on operating conditions such as pH and temperature.

The inclusion of other dyes in this review is important because the direct literature combining areca nut with Bismarck Brown is very limited. Results obtained with another dye should nevertheless not be assumed equivalent to Bismarck Brown, since differences in molecular size, charge, functional groups, aromatic structure, and solution chemistry can significantly affect adsorption behaviour. The review identified one directly relevant study, which examined Bismarck Brown-Y removal using areca husk carbon fibre; it evaluated pH, particle size, and temperature through factorial experimental design and statistical analysis, together with FTIR, XRD, SEM, and EDAX characterization [25].

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A systematic investigation of KOH-treated areca-nut activated carbon specifically for Bismarck Brown removal is therefore required. Such research should connect material preparation and characterization with adsorption optimisation, equilibrium studies, kinetic analysis, thermodynamics, mechanism, and regeneration.

II. ARECA NUT AS A PRECURSOR FOR ACTIVATED CARBON

A. Characteristics of Areca Nut Residues

Areca nut is cultivated extensively in tropical and subtropical regions. Its processing generates several residues, including husk, pod, shell, and fibre, which contain lignocellulosic components and can therefore act as carbonaceous raw materials [12, 16, 18].

Converting areca-nut residues into activated carbon provides a way of utilising agricultural waste while producing an adsorbent for wastewater treatment. Previous research has shown that activated carbon can be prepared from areca-nut pod and husk and subsequently used for adsorption applications [16]. Gopalswami*et al.* prepared activated carbon from areca-nut pod and investigated its application for dye adsorption [16], which supports the basic feasibility of converting areca residues into useful adsorbent materials.

B. Rationale for Using Areca Nut

Several scientific and practical characteristics make areca nut an interesting precursor for activated-carbon production.

Availability of agricultural residue. Areca-nut processing produces considerable quantities of husk, pod, shell, and fibre. These materials may have limited economic value when treated simply as waste, and their conversion into adsorbents provides an additional utilisation route.

Lignocellulosic composition. The cellulose, hemicellulose, and lignin content of areca residues makes them suitable for conversion into carbonaceous materials through thermal treatment [12, 16, 18].

Possibility of chemical activation. Areca residues can be chemically modified using activating agents, which can change surface characteristics and may improve the development of pores and adsorption sites [9, 10].

Surface modification. Alkaline treatment can modify lignocellulosic components and expose additional accessible surface groups, which can affect the interaction between the adsorbent and dissolved dye molecules.

Potential for low-cost adsorbent development. The use of agricultural waste may reduce dependence on commercially manufactured activated carbon. However, a complete economic assessment is required before concluding that a particular areca-based material is cheaper.

Application to different pollutants. Areca-derived materials have already been investigated for several dyes and other pollutants, so their potential is not restricted to a single contaminant [9–17].

III. ROLE OF KOH ACTIVATION

Chemical activation is an important approach for developing porosity in biomass-derived carbon. During activation, the activating chemical interacts with the precursor and can promote structural changes that result in the formation of accessible pores. KOH is one of the most commonly investigated activating agents for preparing porous carbon, and the final surface area and pore structure depend on the precursor, KOH-to-carbon ratio, activation temperature, heating conditions, and activation time.

Studies of KOH-activated biomass show that chemical activation can substantially modify surface area and pore structure. For example, KOH activation of groundnut shell at 600 °C produced an activated carbon with a reported surface area of approximately 412 m^2/g under the investigated conditions. The same activation condition cannot automatically be applied to every biomass because different precursors differ in composition and structure; KOH treatment of areca nut should therefore be experimentally optimised.

Important activation parameters include the KOH-to-biomass (or KOH-to-char) ratio, activation temperature, activation time, heating rate, activation atmosphere, precursor particle size, washing procedure, and final drying conditions.

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Excessive activation may damage the carbon structure or decrease the product yield, so the optimum activation condition should be selected by considering both adsorption performance and material characteristics.

IV. ADSORPTION OF BISMARCK BROWN ON CARBON-BASED ADSORBENTS

Bismarck Brown adsorption has been investigated using several carbon-based and biomass-derived materials, and these studies provide useful background for evaluating a new areca-nut-derived adsorbent. Representative findings are summarised in TABLE I [1, 3–8].

TABLE I: REPORTED BISMARCK BROWN ADSORPTION ON CARBON-BASED AND BIOMASS-DERIVED ADSORBENTS

Adsorbent	Dye	Important findings
Granular activated carbon	Bismarck Brown R	Freundlich equilibrium; pseudo-second-order kinetics; reported spontaneous and endothermic behaviour
Date-seed activated carbon	Bismarck Brown R	Maximum reported capacity around 192.31 mg/g; pseudo-second-order and Elovich models investigated
Acacia nilotica	Bismarck Brown Y	Reported capacity around 40 mg/g under specified conditions; Langmuir model used
Multiwall carbon nanotubes	Bismarck Brown R	Pseudo-second-order kinetics; Langmuir, Freundlich, and Temkin models investigated
Other biomass-derived activated carbons	Bismarck Brown	Demonstrate the potential of agricultural residues as alternative adsorbents

Adsorption performance differs considerably between materials. These differences may result from precursor composition, activation method, pore structure, surface functional groups, dye form, pH, initial concentration, temperature, dosage, and contact time. Adsorption capacities reported in different studies should therefore not be compared without considering their experimental conditions.

V. ADSORPTION OF OTHER DYES USING ARECA-DERIVED MATERIALS

Although Bismarck Brown is the principal target dye of this review, investigating only one dye would provide limited information about the versatility of areca-derived adsorbents. Areca-nut-derived materials have been investigated for Methylene Blue, Brilliant Green, direct dyes, Methyl Orange, Rhodamine B, Alizarin Red S, heavy-metal ions, and pharmaceutical compounds.

Sodium-hydroxide-treated areca-nut husk has been investigated for Brilliant Green removal; under the reported optimum conditions, approximately 97% dye removal was obtained with a maximum adsorption capacity of about 18.21 mg/g [9]. Areca-husk-derived activated carbon has also been investigated for Methylene Blue removal using FTIR, BET, SEM, and pH_{pzc} analysis [15–17]. More recent work on activated carbon and carbon quantum dots derived from areca-nut husk reported approximately 193.80 mg/g for Methylene Blue in one activated-carbon system [17], and magnetic biochar prepared from waste areca-nut husk reached approximately 785.3 mg/g for Methylene Blue [15]. These results indicate that modification of areca biomass can produce materials with substantially different adsorption performances.

Results obtained with other dyes should nevertheless be treated as supporting rather than direct evidence for Bismarck Brown removal, because dye charge, molecular structure, molecular size, aromaticity, and functional groups can influence adsorption significantly. The main purpose of studying other dyes is to understand the general adsorption potential of areca-derived materials and to identify suitable modification strategies.

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VI. PROPOSED MATERIALS AND METHODS

A systematic experimental design is required to evaluate KOH-treated areca-nut activated carbon for Bismarck Brown removal. Rather than measuring dye removal under one set of conditions, the important preparation and operating variables should be investigated systematically. The framework described in this section is proposed and has not been experimentally executed in this review. It comprises preparation of areca-derived activated carbon, KOH treatment and activation, characterization, preparation of Bismarck Brown solutions, batch adsorption experiments, evaluation of pH, dosage, initial concentration, contact time, particle size, and temperature, kinetic, isotherm, and thermodynamic modelling, statistical optimisation, and regeneration and reusability studies.

A. Selection and Preparation of Areca Nut

Areca-nut husk or another suitable residue can be selected as the precursor. The collected material should be cleaned thoroughly with water to remove soil, dust, and other foreign substances, then dried and reduced to a relatively uniform particle size by grinding and sieving. Raw and modified samples can be prepared separately so that the effects of chemical treatment and thermal activation on surface chemistry, morphology, porosity, and adsorption performance can be compared.

B. KOH Treatment and Thermal Activation

The prepared areca material can be treated with potassium hydroxide (KOH) under controlled conditions. KOH is selected because alkaline activation can modify the lignocellulosic structure and promote the formation of pores and accessible adsorption sites. A predetermined quantity of areca-nut material is mixed with a KOH solution of the required concentration and maintained under controlled conditions to allow sufficient interaction. The material is then separated, washed repeatedly with distilled or deionised water to remove excess alkali, and dried before thermal activation.

The KOH-treated material can subsequently undergo pyrolysis or thermal activation, during which volatile components are removed and a carbon-rich porous structure develops. Different activation temperatures can be investigated because temperature influences carbonisation, pore formation, surface area, functional groups, carbon structure, and final adsorption capacity; temperature and holding time should be kept consistent for comparative experiments. After cooling, the carbon is washed repeatedly with distilled water, possibly until the wash water approaches neutral pH, then dried, ground, sieved, and stored in a clean, dry, airtight container. For reproducible preparation, the KOH concentration, biomass-to-KOH ratio, activation temperature, heating rate, activation time, particle size, washing procedure, and final drying conditions should be clearly reported, because these parameters strongly influence surface area, pore structure, functional groups, and adsorption capacity.

C. Preparation and Quantification of Bismarck Brown Solutions

A stock solution of known Bismarck Brown concentration should be prepared using distilled or deionised water, and working concentrations obtained by suitable dilution. UV–Visible spectrophotometry can be used to determine the dye concentration remaining after adsorption; a calibration curve should first be prepared using standard solutions of known concentration, and the relationship between absorbance and concentration used to determine unknown samples. The percentage dye removal is calculated as

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

and the equilibrium adsorption capacity as

$$q_e = [(C_0 - C_e) \times V] / m \qquad (2)$$

where C_0 is the initial dye concentration (mg/L), C_e is the equilibrium dye concentration (mg/L), q_e is the equilibrium adsorption capacity (mg/g), V is the volume of dye solution (L), and m is the mass of adsorbent (g).

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D. Batch Adsorption Experiments

Batch adsorption is suitable for studying individual operating variables under controlled laboratory conditions. A known quantity of adsorbent is added to a known volume and concentration of Bismarck Brown solution, and the mixture is agitated for a predetermined period at a controlled temperature. The adsorbent is then separated by filtration or centrifugation, and the remaining dye concentration is determined by UV–Visible spectrophotometry. The major variables are initial dye concentration, adsorbent dosage, solution pH, contact time, temperature, particle size, and activation condition.

E. Effect of pH

The pH can change both the surface charge of the adsorbent and the chemical form or charge characteristics of the dye. A suitable pH range should be tested while keeping other conditions constant, and the optimum pH identified from the condition producing the desired adsorption performance. The pH results should be interpreted together with pH_{pzc} and FTIR information to understand possible electrostatic interactions.

F. Effect of Adsorbent Dosage

Different quantities of activated carbon should be added to the same volume and concentration of Bismarck Brown solution. Increasing the adsorbent amount generally increases the number of available adsorption sites and may increase the percentage removal, whereas adsorption capacity per unit mass may behave differently. Both percentage removal and adsorption capacity should therefore be considered when selecting an optimum dosage.

G. Effect of Initial Dye Concentration and Isotherm Studies

Experiments should be carried out at different initial Bismarck Brown concentrations while maintaining constant adsorbent dosage, pH, temperature, and contact time. This shows how adsorption behaves at different pollutant concentrations, and the resulting equilibrium data should be fitted to suitable isotherm models. The Langmuir model assumes adsorption on a finite number of sites and is commonly used to estimate maximum adsorption capacity, whereas the Freundlich model is generally used to describe adsorption on heterogeneous surfaces where sites may possess different energies. Comparison of the models indicates which mathematical description is more appropriate for the experimental data.

H. Effect of Contact Time and Adsorption Kinetics

Samples should be collected at different time intervals until adsorption equilibrium is reached, and the remaining Bismarck Brown concentration measured spectrophotometrically. The data can be analysed using pseudo-first-order, pseudo-second-order, Elovich, and intraparticle-diffusion models, which provide information about the adsorption rate and possible rate-controlling processes.

I. Effect of Temperature and Thermodynamic Analysis

Adsorption experiments can be conducted at different temperatures to investigate the influence of temperature on Bismarck Brown uptake. The Gibbs free-energy change (ΔG), enthalpy change (ΔH), and entropy change (ΔS) can be calculated from equilibrium data and provide information on the spontaneity and energetic nature of adsorption. Temperature experiments should be performed under carefully controlled conditions so that observed changes can primarily be associated with temperature.

J. Statistical Experimental Design and Optimization

A statistical experimental-design approach can be used instead of changing only one factor at a time. Factorial design or response surface methodology (RSM) can be used to study the individual and combined effects of variables such as pH, adsorbent dosage, particle size, temperature, initial dye concentration, and contact time. The directly relevant

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areca-husk/Bismarck Brown study identified in this review used a 2^3 factorial design to examine pH, particle size, and temperature, with ANOVA, *t*-tests, and *F*-tests for statistical analysis [25]. Similar methods can be extended in future investigations to include additional variables and their interactions.

K. Comparison with Other Dyes

Bismarck Brown should remain the primary target dye, but selected other dyes (Methylene Blue, Brilliant Green, Methyl Orange, Rhodamine B, and Alizarin Red S) may be investigated for comparison. The purpose is to determine how the areca-derived adsorbent behaves toward dyes with different molecular structures and charge characteristics; adsorption of several of these dyes using areca-based materials has already been demonstrated [9–11, 15–17].

L. Regeneration and Reusability

The ability to regenerate and reuse an adsorbent is important for practical wastewater treatment. After adsorption, the spent adsorbent can be subjected to a suitable desorption or regeneration process and then used in another adsorption cycle. For each cycle, the dye removal percentage, adsorption capacity, loss of performance, and regeneration efficiency should be recorded, and the changes over repeated cycles analysed to determine practical reusability.

M. Proposed Experimental Sequence

The overall sequence can be arranged as: areca nut collection, cleaning, drying, grinding/sieving, KOH treatment, thermal activation/carbonisation, washing, drying, characterization, Bismarck Brown solution preparation, calibration curve, batch adsorption, optimisation of operating conditions, kinetic study, isotherm study, thermodynamic study, regeneration/reusability, and mechanism analysis. This framework connects material preparation with characterization, process optimisation, adsorption modelling, and regeneration, and can help generate the detailed experimental information that is currently limited for the direct areca-nut/Bismarck Brown system.

VII. CHARACTERIZATION OF THE ADSORBENT UNDER OPTIMUM CONDITIONS

The adsorbent should be characterized before adsorption to understand its physical and chemical properties, and selected techniques should be repeated after Bismarck Brown uptake to determine the resulting changes. Once the optimum adsorption conditions have been determined, characterization helps explain why the adsorbent performs effectively, because maximum dye removal alone cannot explain the complete adsorption behaviour. It relates performance to surface functional groups, morphology, pore structure, elemental composition, surface area, and surface charge.

A. FTIR Analysis

Fourier-transform infrared spectroscopy (FTIR) should be used to identify functional groups on the adsorbent, and spectra before and after Bismarck Brown adsorption should be compared. Changes in peak position or intensity can indicate involvement of particular functional groups, such as hydroxyl, carbonyl, carboxyl, and other oxygen-containing groups, and can provide supporting evidence for hydrogen bonding, electrostatic interactions, and surface complexation. FTIR results should be interpreted together with other characterization and adsorption data rather than used alone to establish a mechanism.

B. SEM Analysis

Scanning electron microscopy (SEM) should be used to investigate the surface morphology of the optimum adsorbent, including pores, cavities, cracks, surface roughness, and irregular surface structures. Surfaces should be compared before and after adsorption, since morphological changes may indicate the presence or retention of dye molecules. A developed and accessible porous structure may provide greater contact between dye molecules and adsorption sites.

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C. EDX/EDAX Analysis

Energy-dispersive X-ray analysis (EDX/EDAX), usually performed together with SEM, determines the elemental composition of the adsorbent. Compositions before and after adsorption should be compared, as the appearance or increase of elements associated with Bismarck Brown can provide additional evidence of dye retention. EDX should be considered supporting evidence rather than standalone proof of adsorption.

D. XRD Analysis

X-ray diffraction (XRD) can be used to determine whether the material is predominantly crystalline, amorphous, or a combination of both. Comparison between the original areca precursor and the activated material can reveal structural changes caused by KOH treatment, carbonisation, and activation, and XRD after adsorption can show whether Bismarck Brown uptake produces detectable structural changes.

E. BET Surface Area and Pore Analysis

BET analysis should be performed to determine the specific surface area, pore volume, and pore-size characteristics of the optimum adsorbent. A developed porous structure can increase the accessible surface available for interaction with Bismarck Brown molecules, and pore characteristics also indicate the possible contribution of pore filling. However, surface area alone should not be considered the reason for high adsorption capacity, because adsorption also depends on surface chemistry, functional groups, pore accessibility, pore-size distribution, dye molecular dimensions, and electrostatic interactions.

F. Point of Zero Charge (pH_{pzc})

The point of zero charge (pH_{pzc}) should be determined because the surface charge of the adsorbent can strongly influence its interaction with dye molecules. The relationship between solution pH and pH_{pzc} can help explain the pH dependence observed during adsorption experiments and is particularly useful for evaluating possible electrostatic attraction or repulsion between Bismarck Brown and the adsorbent surface.

G. Comparison Before and After Adsorption

The most informative strategy is to compare the optimum adsorbent before and after Bismarck Brown adsorption, as summarised in TABLE II. Such comparison provides stronger evidence for understanding the adsorption process.

TABLE II: BEFORE-AND-AFTER CHARACTERIZATION STRATEGY FOR THE OPTIMUM ADSORBENT

Technique	Before adsorption	After adsorption	Purpose
FTIR	Surface functional groups	Changes in absorption bands	Identify groups potentially involved in adsorption
SEM	Initial morphology and pores	Surface changes after dye uptake	Examine morphological changes
EDX	Initial elemental composition	Changes in elemental composition	Support evidence of dye retention
XRD	Initial structural properties	Structural changes	Examine structural behaviour
BET	Surface area and pore characteristics	Changes where measurable	Relate porosity to adsorption

VIII. ADSORPTION MECHANISM

Adsorption of Bismarck Brown onto KOH-treated areca-nut activated carbon is likely to involve more than one interaction. The possible mechanisms are discussed below; they are proposed on the basis of the literature and require experimental confirmation.

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A. Electrostatic Interactions

Electrostatic attraction or repulsion can occur between charged dye species and charged sites on the adsorbent surface. Its importance depends on solution pH, pH_{pzc}, dye charge characteristics, and surface functional groups, so pH experiments and pH_{pzc} measurements are important for interpreting these interactions.

B. Hydrogen Bonding

Hydrogen bonding may occur between functional groups on Bismarck Brown and oxygen-containing groups (hydroxyl, carbonyl, carboxyl, and related groups) on the carbon surface. Changes in FTIR bands before and after adsorption can provide supporting evidence.

C. π–π Interactions

Bismarck Brown contains aromatic structures, while activated carbon can contain aromatic and graphitic carbon domains. Interactions between the π-electron systems of the dye and the carbon surface may contribute to adsorption, particularly for carbonaceous adsorbents with developed aromatic structures.

D. Pore Filling

Bismarck Brown molecules can enter accessible pores within the activated carbon. Pore filling depends on pore-size distribution, pore accessibility, dye molecular dimensions, and surface area, so BET analysis provides useful information when evaluating this mechanism.

E. Surface Complexation

Specific interactions can occur between dye molecules and functional groups located on the adsorbent surface, which may involve oxygen-containing groups or other chemically active sites. FTIR and other surface-characterization techniques can help investigate such interactions.

F. Van der Waals Interactions

Weak physical interactions between dye molecules and the carbon surface can also contribute to total adsorption. The actual mechanism should therefore be considered a combination of several possible interactions rather than attributed to only one, and the relative importance of each should be established from experimental evidence obtained from characterization, pH studies, adsorption models, and other results.

IX. CONCLUSION

This review demonstrates the potential of areca-nut-derived materials as renewable and potentially low-cost adsorbents for treating dye-contaminated wastewater. Areca nut residues (husk, pod, shell, and fibre) contain cellulose, hemicellulose, and lignin and can be converted into value-added adsorbents such as biosorbents, biochar, activated carbon, carbon fibres, carbon nanospheres, magnetic biochar, and composite materials [9–17]. Using these residues for adsorption links agricultural-waste management with wastewater treatment.

Previous studies have demonstrated adsorption of several dyes using areca-derived materials, including Methylene Blue, Brilliant Green, Methyl Orange, Rhodamine B, and Alizarin Red S [9–11, 15–17], and indicate that chemical treatment, pyrolysis, activation, and magnetisation can substantially change adsorption behaviour. Performance nevertheless varies with the precursor, modification procedure, surface properties, pollutant structure, pH, temperature, initial concentration, adsorbent dosage, and contact time.

Bismarck Brown is a comparatively less investigated target for areca-derived adsorbents; only one directly relevant study, involving areca husk carbon fibre and Bismarck Brown-Y, was identified [25]. This is considerably fewer direct studies than those available for areca-based adsorbents with other dyes or for Bismarck Brown with other adsorbents. The existing literature therefore supports the general potential of areca-nut-derived materials but does not provide sufficient direct evidence to establish the performance of KOH-treated areca-nut activated carbon toward Bismarck Brown. Studies of other Bismarck Brown adsorbents, including activated carbon, agricultural wastes, mesoporous materials, carbon nanotubes, polymeric adsorbents, graphene-based materials, and inorganic nanomaterials, show that adsorption can be an effective removal approach [1–8, 20–24], although direct comparison of capacities is difficult because experimental conditions and material properties differ.

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The adsorption mechanism may involve electrostatic attraction, hydrogen bonding, π–π interactions, pore filling, surface complexation, and van der Waals interactions. FTIR, SEM–EDX, XRD, BET, and pH_{pzc} analysis can provide evidence for these mechanisms, but the mechanism should be established from experimental results rather than assumed from studies involving other dyes.

The major research opportunity identified is the systematic preparation and evaluation of areca-nut-derived activated carbon for Bismarck Brown removal. Future work should compare untreated and chemically modified areca materials and investigate the influence of preparation and operating parameters. The programme should include preparation and characterization of KOH-treated activated carbon; preparation of Bismarck Brown standards and a UV–Visible calibration curve; batch experiments optimising pH and adsorbent dosage and examining initial concentration, contact time, particle size, and temperature; kinetic modelling (pseudo-first-order, pseudo-second-order, Elovich, and intraparticle-diffusion), isotherm modelling (Langmuir and Freundlich), and thermodynamic analysis (ΔG, ΔH, and ΔS); characterization before and after adsorption; mechanism investigation; and regeneration and reusability studies, since practical usefulness depends not only on initial capacity but also on performance retained after repeated use.

The main limitation of the existing literature is the small number of direct studies combining areca-derived adsorbents with Bismarck Brown, and different studies do not always provide comparable capacity, equilibrium, kinetic, thermodynamic, regeneration, and characterization data. Results for other dyes should not be assumed to represent Bismarck Brown behaviour because dyes differ in molecular structure, charge, size, and functional groups. Overall, areca nut is a promising agricultural-waste precursor for sustainable adsorbents, but the specific use of KOH-treated areca-nut activated carbon for Bismarck Brown removal remains insufficiently studied. A systematic study combining preparation, detailed characterization, adsorption optimisation, equilibrium, kinetic, and thermodynamic analysis, mechanism evaluation, and regeneration would help address this gap and determine the practical potential of the material.

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IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 6, Issue 2, October 2026 Impact Factor: 8.2

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