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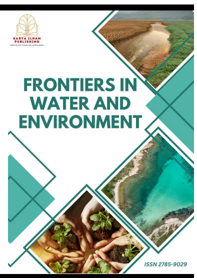

Activated Nanomagnetic Biochar for Dye Adsorption: A Recent Systematic Review

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ABSTRACT

The increasing demand for efficient and sustainable water treatment technologies has driven significant interest in the development of Activated Nanomagnetic Biochar (ANBC) for dye adsorption. However, despite the growing body of research, a comprehensive synthesis of current advancements remains limited. This Systematic Literature Review (SLR) aims to consolidate and critically analyze the existing studies on this emerging material. Adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, an extensive search was conducted across two major databases, Web of Science and Scopus, resulting in 26 Primary Studies (PS) that met the inclusion criteria. The selected studies were systematically categorized into three major research themes: (1) synthesis and characterization of magnetic nanocomposites, focusing on the methods and techniques used to fabricate and analyze ANBC; (2) adsorption and removal of dyes, which examines the performance metrics and mechanisms of dye adsorption under various environmental conditions; and (3) environmental and sustainable applications, highlighting the role of ANBC in promoting eco-friendly and scalable wastewater treatment solutions. The findings reveal that advances in synthesis techniques and surface modifications have significantly enhanced the adsorption capacities and reusability of these materials. The integration of magnetic properties facilitates separation and recovery from aqueous systems, though scalability and long-term stability under field conditions require further investigation. Nevertheless, challenges related to large-scale production, long-term stability, and environmental safety persist. This review identifies current research gaps and provides insights into future directions for the development of next-generation biochar-based materials for sustainable water remediation.

1. Introduction

The persistent presence of synthetic dyes in industrial effluents, particularly from textile, leather, and paper manufacturing, poses a significant environmental and public health challenge [1-5]. These

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dyes, many of which are toxic, carcinogenic, and resistant to biodegradation, can contaminate aquatic ecosystems even at trace concentrations, disrupting photosynthesis and posing a threat to both aquatic and human life [6-10]. Both cationic and anionic dyes are of particular concern due to their high chemical stability and complex aromatic structures [11,12]. Conventional treatment technologies such as coagulation, flocculation, advanced oxidation, and membrane filtration often fall short due to high costs, limited efficiency, and the generation of secondary pollutants [13,14], [15-18]. In contrast, adsorption has emerged as a cost-effective and operationally simple alternative, offering high removal efficiency and minimal environmental impact [19-23]. Biochar, a carbon-rich material derived from the pyrolysis of biomass, has attracted significant attention in this context for its tunable surface chemistry, porosity, and environmental sustainability [22-25]. Modifying biochar with magnetic nanoparticles further enhances its functionality, enabling rapid separation and reuse via magnetic retrieval, contributing to the development of efficient and regenerative adsorbents for wastewater treatment [26-29] .

Despite considerable progress, several critical challenges remain unresolved in the application of magnetic biochar for dye adsorption [30-34]. Most studies have focused on removing either cationic or anionic dyes individually, with limited attention given to materials capable of adsorbing both types simultaneously under practical conditions. Additionally, magnetic modifications are often applied without fully optimizing key structural features such as pore architecture, surface area, and the density of functional groups, which are essential for maximizing adsorption capacity [35-37]. The synergistic effects between magnetic components and activated biochar surfaces, particularly with adsorption mechanisms like electrostatic interactions, ion exchange, and π-π stacking, remain insufficiently understood [38-42]. This research addresses these gaps by developing an Activated Nanomagnetic Biochar (ANBC) using a combined activation and magnetization strategy. The primary objective is to evaluate its dual adsorption capacity for representative cationic and anionic dyes, assess the kinetics and equilibrium behavior, and investigate the material's regeneration potential. This work aims to provide deeper insights into structure-performance relationships and to guide the design of next-generation multifunctional adsorbents for comprehensive and scalable wastewater remediation solutions.

1.1 Literature Review

Recent developments in the synthesis of ANBC highlight its promising role in dye adsorption, with a particular focus on both cationic and anionic contaminants. A diverse range of biomass feedstocks, including goat dung [43], palm kernel shells [44], and egg white biomass [45], has been explored to create cost-effective and sustainable adsorbents. Thangamani *et al*., [43] demonstrated that Goat Dung-derived Activated Carbon doped with Cobalt Ferrite Magnetic Composite (GDAC-CFMC) exhibited efficient adsorption of anionic dyes such as Direct Brown 2 and Reactive Red 152 under acidic conditions, with adsorption governed by the Freundlich isotherm and pseudo-second-order kinetics. Waluyo *et al*., [44] compared single- and multi-step pyrolysis of palm kernel shells, finding that multi-step activation improved pore size and enhanced adsorption of Methyl Orange (MO). Vahdati-Khajeh *et al*., [45] incorporated sucrose into egg white-derived hydrochar, yielding nitrogen-rich Magnetic Activated Carbon (MAC) with high Methylene Blue (MB) adsorption. These studies highlight the adaptability of ANBC feedstocks, though varying activation (e.g., $ZnCl_2$, KOH) and magnetization techniques (e.g., Fe_3O_4, $CoFe_2O_4$) yield different physicochemical profiles and adsorption efficiencies.

Furthermore, the integration of magnetic nanoparticles enhances ANBC recoverability, allowing for post-adsorption separation using external magnetic fields. Thangamani *et al*., [43] demonstrated that GDAC-CFMC's strong magnetization (33.5 emu/g) facilitated easy retrieval. Taghdiri [46] developed a composite MAC coating with silicotungstic acid, enhancing the selectivity of MB and enabling photocatalytic degradation under sunlight. Nevertheless, excessive magnetic loading can reduce surface area. Vahdati-Khajeh *et al*., [45] observed reduced porosity due to iron oxide aggregation. These trade-offs necessitate optimized nanoparticle dispersion. Taghdiri [46] also highlighted the dual function of photocatalysis and adsorption, though such hybrid applications remain underexplored in ANBC research.

Adsorption mechanisms vary depending on the type of dye and the properties of the biochar. Thangamani *et al*., [43] attributed anionic dye uptake to electrostatic attraction and surface complexation, which was well-fitted by the Freundlich model. In contrast, Waluyo *et al*., [44] reported that MO adsorption on MAC followed the Redlich–Peterson model, suggesting a combination of monolayer and multilayer adsorption. Taghdiri [46] observed preferential MB adsorption in mixed-dye systems, influenced by dye charge and molecular size. Surface chemistry and pH-dependent charge play crucial roles in adsorption pathways, while kinetic studies mostly align with pseudo-second-order models [43,44], indicating chemisorption. However, diffusion may dominate in macroporous structures.

The regeneration and reusability of ANBCs are key to their scalability. Waluyo *et al*., [44] achieved a 98.34% desorption efficiency using NaOH. Taghdiri [46] reported 80% regeneration efficiency via photocatalytic ultraviolet (UV) treatment after five cycles. Thangamani *et al*., [43] noted 85% retention of adsorption capacity in regenerated GDAC-CFMC, though thermal stability declined at higher temperatures. Regeneration outcomes depend on the adsorbent's dye binding strength and the employed method. Nonetheless, long-term stability under real wastewater conditions is affected by competing ions, and pH fluctuations remain underexamined.

Despite advances, several critical gaps persist. Most studies focus on single-dye systems [43,45], overlooking the complex industrial effluents that contain mixed dyes. Environmental implications of chemical activators such as $ZnCl_2$ and KOH, although widely used, are seldom assessed [44]. Standardization of magnetic nanoparticle loading and activation protocols is needed to enable comparative analyses. Future research should prioritize multifunctional ANBCs for the simultaneous removal of cationic and anionic dyes and validate their efficacy in pilot-scale applications.

In addition to agricultural feedstocks, other biomass sources have been leveraged for ANBC synthesis. Rong *et al*., [47] employed co-precipitation to produce MAC from coal-derived precursors, achieving a high Brunauer–Emmett–Teller (BET) surface area and γ-Fe_2O_3 as the dominant magnetic phase. Rezaei Kalantry *et al*., [48] integrated iron oxide into activated carbon, yielding rapid separation and structural stability (Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD)). Elshimy *et al*., [49] used eggshell waste with Fe_3O_4 and sodium alginate to produce spherical, porous bio-based MACs. These efforts confirm the versatility of ANBC synthesis, though disparities in activation agents (NaOH, Na_2SiO_3) and magnetic precursors ($FeCl_3$) influence structural and functional outcomes. A persistent limitation is the lack of standardized protocols for balancing magnetic content and adsorption performance.

Moreover, dye ionicity, surface functional groups, and pH conditions drive adsorption efficiency. Rong *et al*., [47] reported strong malachite green adsorption (766 mg/g) via electrostatic interaction at alkaline pH, fitting the Freundlich model. Rezaei Kalantry *et al*., [48] observed Langmuir behavior for Reactive Blue 5, indicating monolayer chemisorption. Yadav *et al*., [50] developed a Fe_3O_4/β-cyclodextrin/activated charcoal composite, exhibiting dual Langmuir–Temkin behavior for cationic dyes. While these studies highlight diverse adsorption pathways, most neglect competitive adsorption in mixed-dyed systems, a significant limitation for real-world applications.

ANBC regeneration studies support its potential for reuse. Rong *et al*., [47] achieved 93.6% regeneration using desorption agents, though capacity declined at high temperatures. Yadav *et al*., [50] maintained >70% efficiency over four ethanol-regeneration cycles. Elshimy *et al*., [49] reported 71–74% removal over four cycles, with structural integrity confirmed by Transmission Electron Microscopy (TEM). However, the effects of organic matter, salinity, and other complexities of real wastewater remain underexplored. Note that energy-intensive and chemical regeneration methods also pose sustainability concerns.

Further studies are essential to bridge existing gaps. Emphasis should be placed on multifunctional ANBCs for mixed dye systems [51,52], green activation methods [53], and real effluent trials. Standardized life cycle and toxicity analyses will be pivotal for sustainable scale-up.

2. Methodology

In order to conduct an SLR, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework introduced by Page *et al*., [54] is widely recognized as the gold standard. It helps ensure the review process is clear, thorough, and consistent from start to finish. By following PRISMA's structured guidelines, researchers can carefully identify, select, and include studies in a way that enhances both the accuracy and integrity of their analysis. The framework also emphasizes the importance of randomized studies, which are particularly effective in minimizing bias and strengthening the overall evidence. For this review, two well-established databases, the Web of Science and Scopus, were selected due to their comprehensive coverage and reliability.

2.1 Identification

In this study, a structured approach was taken to gather a substantial body of relevant literature for the systematic review. The process began with selecting core keywords, which were then expanded by exploring related terms using dictionaries, thesauri, encyclopedias, and insights from previous research. Once a comprehensive list of search terms was compiled, tailored search strings were created for use in the Web of Science (WoS) and Scopus databases (as outlined in Table 1). This initial search yielded a total of 517 publications related to the study's focus from both databases.

Table 1
The search string

Databases	Search string
Scopus	TITLE-ABS-KEY (activate* AND (magnetic OR nanomagnetic) AND dye* AND adsorption OR biochar) AND (LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "MATE") OR LIMIT-TO (SUBJAREA , "CHEM") OR LIMIT-TO (SUBJAREA , "AGRI")) AND (LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024) OR LIMIT-TO (PUBYEAR , 2025)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (PUBSTAGE , "final")) Date of Access: May 2025
WoS	activated AND nanomagnetic AND dye AND adsorption (Topic) and 2024 or 2023 (Publication Years) and Article (Document Types) and English (Languages) and Chemistry or Environmental Sciences Ecology or Science Technology Other Topics or Water Resources (Research Areas) and 2024 or 2023 (Publication Years) and Article (Document Types) and English (Languages) Date of Access: May 2025

2.2 Screening

In the first stage of screening, 420 publications were excluded because they did not meet the basic relevance or quality thresholds. This left 97 papers, which were then subjected to a more detailed review using refined inclusion and exclusion criteria (outlined in Table 2). The primary criterion prioritized original research papers, as they offer direct, practical insights that are crucial for this study. Additionally, secondary sources such as reviews, meta-syntheses, meta-analyses, books, book series, chapters, and conference proceedings were excluded if they were not deemed highly relevant or outdated. To refine the selection, only publications written in English were considered, ensuring consistency and accessibility of interpretation. Moreover, the review was limited to studies published between 2023 and 2025 to maintain a focus on the most recent advancements. Altogether, this structured and selective approach helped ensure that only the most relevant and high-quality studies were included for the subsequent stages of the systematic review.

Table 2
The selection criterion is searching

Criterion	Inclusion	Exclusion
Language	English	Non-english
Timeline	2023 – 2025	< 2023
Literature type	Journal (article)	Conference, book, review
Publication stage	Final	In Press
Subject area	Chemistry, Environmental Science, Materials Science, Agricultural and Biological Sciences	Besides Chemistry, Environmental Science, Materials Science, Agricultural and Biological Sciences

2.3 Eligibility

In the eligibility stage of the review process, a total of 97 articles were carefully examined. Each article’s title, abstract, and main content were reviewed to determine whether they met the inclusion criteria. Articles were excluded for several reasons: being outside the field of study, having titles that were not significantly related to the research focus, presenting abstracts that did not align with the study’s objectives, or lacking full-text access. As a result of this thorough screening, 71 articles were excluded from the review. Following this exclusion process, 26 articles were deemed suitable and included for quantitative analysis (outlined in Table 3). These selected studies formed the core foundation for the next phase of the review, where detailed examination and thematic synthesis were conducted. By narrowing down to only the most relevant and accessible research, the review ensured a focused and high-quality analysis that directly addressed the study’s objectives.

Table 3
Number and details of primary studies database

No	Authors	Title	Journal	Scopus	WoS
1	[55]	Facile synthesis of magnetic-activated nanocomposites for effective removal of cationic and anionic dyes in an aqueous environment: An equilibrium isotherm, kinetics and thermodynamic studies	Chemical Engineering Research and Design	/	
2	[56]	Bio-based activated carbon from husk-and wood-based biomass: comparison of carbon activation methods on organic pollutants removal	Water Practice and Technology	/	
3	[57]	Magnetic porous carbon nanocomposites derived from cactus (*Opuntia stricta Haw*.) for the removal of toxic dyes: optimization of synthesis conditions using response surface methodology	Journal of Chemical Technology and Biotechnology	/	
4	[58]	Adsorption of Rhodamine B, methyl Orange, and phenol separately in aqueous systems by magnetic activated carbon: Optimization by central composite design	Materials Science and Engineering: B	/	
5	[59]	Chemical activation and magnetization of carbonaceous materials fabricated from waste plastics and their evaluation for methylene blue adsorption	Environmental Science and Pollution Research	/	
6	[60]	Facile Synthesis of Citric Acid Functionalized Fe_3O_4@Activated Carbon Magnetic Nanocomposite for Efficient Adsorption of Brilliant Green Dye from Wastewater	Chemistry Select	/	
7	[61]	Magnetic iron-oxide coffee husk and khat waste biochar nanocomposites for removal of methylene blue from aqueous solution	Separation Science Plus	/	
8	[62]	Recyclable magnetic Fe_3O_4@C for methylene blue removal under microwave-induced reaction system	Chemosphere	/	
9	[63]	Synthesis of novel magnetic activated carbon for effective Cr (VI) removal via synergistic adsorption and chemical reduction	Environmental Technology and Innovation	/	
10	[64]	Removal of methyl orange and methylene blue from wastewater by magnetic nanocomposites loaded activated carbon synthesized from walnut shell	Indian Journal of Chemical Technology	/	
11	[65]	In-situ magnetic activated carbon produced from sludge, straw and steel slag for the effective adsorption of methylene blue	Desalination and Water Treatment	/	
12	[66]	Methylene blue and methyl orange removal from wastewater by magnetic adsorbent based on activated carbon synthesized from watermelon shell	Desalination and Water Treatment	/	
13	[67]	Fabrication of magnetic activated carbon from corn-cob biomass for the removal of acidic dyes from wastewater	Desalination and Water Treatment	/	

14	[68]	A study on the role of surface functional groups of metakaolin in the removal of methylene blue: Characterization, kinetics, modeling and RSM optimization	Environmental Research	/	
15	[69]	Magnetic activated carbon for the removal of methyl orange from water via adsorption and Fenton-like degradation	Particuology	/	
16	[70]	Synthesis, characterization, and valorization of Fe_3O_4/AC nanocomposite for adsorptive removal of crystal violet (CV) from aqueous solution	Journal of Porous Materials	/	
17	[71]	One-step synthesis of magnetic asphalt-based activated carbon with high specific surface area and adsorption performance for methylene blue	Separation and Purification Technology	/	
18	[72]	Magnetite/activated sludge hybrid process for the treatment of dye containing simulated textile wastewater	Desalination and Water Treatment	/	
19	[73]	Magnetic Carbon Nanocomposites: Preparation from Cellulose via Chemical Activation with $FeCl_3$ and Characterization	Russian Journal of Inorganic Chemistry	/	
20	[74]	Development of Highly Efficient Heterogeneous Fe_3O_4-Biochar Nanocomposite as Fenton-like Catalysts for Degradation of Fast Green	ChemistrySelect	/	
21	[75]	Kinetics and thermodynamics investigations of efficient and eco-friendly removal of alizarin red S from water via acid-activated Dalbergia sissoo leaf powder and its magnetic iron oxide nanocomposite	Frontiers in Chemistry	/	
22	[76]	Combination of magnetic activated carbon and activated sludge for methylene blue and nickel (II) ions removal in aerobic biological treatment	Vietnam Journal of Chemistry	/	
23	[77]	Macroscopic and Microscopic Levels of Methylene Blue Adsorption on a Magnetic Bio-Based Adsorbent: In-Depth Study Using Experiments, Advanced Modeling, and Statistical Thermodynamic Analysis	Magnetochemistry	/	
24	[78]	A sustainable and fast methodology based on magnetic activated carbon for removal of imidacloprid from aqueous solution	Journal of Environmental Chemical Engineering	/	
25	[79]	Exploring the structural characteristics and dye removal capabilities of powder-, granule- and film- shaped magnetic activated carbon derived from Oleaster seed	Environmental Science and Pollution Research	/	
26	[80]	Cd (II) Sorption by Nanomagnetic Aerogels Modified with Bentonite and Activated Carbon	Environmental Engineering Science		/

2.4 Data Abstraction and Analysis

In this study, an integrative analysis approach was employed to assess and synthesize a range of research designs, primarily focusing on quantitative methods. The main objective was to uncover key topics and subtopics relevant to the field. The process began with data collection, which laid the foundation for developing the study's main themes. As illustrated in Figure 1, the authors carefully reviewed 26 selected publications, examining statements and information that directly related to the research focus. Following this, they evaluated significant studies on activated nanomagnetic dye adsorption, paying close attention to the methodologies used and the findings reported.

Throughout the analysis, the authors collaborated closely to identify and refine key themes, ensuring that all interpretations were grounded in the evidence. To maintain transparency and thoroughness, a log was kept during the entire data analysis process, capturing reflections, observations, challenges, and insights that emerged along the way. Finally, the authors compared their interpretations to check for any inconsistencies in the theme development. If any disagreements arose, they were openly discussed and resolved through collaborative dialogue, ensuring a shared understanding and consistency in the results.

Finally, the developed themes were refined to ensure consistency and coherence. Two experts conducted the examinations to ensure the validity of the problems. The expert review phase facilitated the assessment of each sub-theme's clarity, significance, and sufficiency by establishing domain validity. Modifications have been implemented at the author's discretion, informed by expert feedback and comments.

3. Results and Findings

3.1 Theme 1: Synthesis and Characterization of Magnetic Nanocomposites

The synthesis of magnetic-activated nanocomposites has garnered considerable attention for their efficiency in adsorbing various dyes from aqueous solutions. Li *et al.*, [55] successfully enhanced the surface area and porosity of eucalyptus carbon through simultaneous magnetization with K_2CO_3 and $FeCl_3$, leading to significantly improved adsorption capacities for MO and MB. Similarly, Nguyen *et al.*, [57] developed $ZnFe_2O_4$-loaded activated carbon from Opuntia stricta and achieved high adsorption capacities for Rhodamine B (RhB), MO, and Acid Yellow 17 (AY), demonstrating efficient dye removal performance after optimization via response surface methodology. Singh *et al.*, [60] also reported a highly efficient dye removal process using citric acid-functionalized Fe_3O_4@activated carbon, with a maximum adsorption capacity of 773 mg/g for brilliant green dye, emphasizing the role of electrostatic interactions and hydrogen bonding. These studies collectively highlight the effectiveness of modifying biomass-derived activated carbons to improve their dye adsorption capabilities.

In another approach, the synergistic use of adsorption and chemical reduction mechanisms was explored. Wu *et al.*, [63] synthesized Fe_3O_4@AC from commercial activated carbon for Cr (VI) removal, achieving a maximum adsorption capacity of 45.3 mg/g. The adsorption behavior, as fitted to pseudo-second-order kinetics and Langmuir isotherm models, revealed a spontaneous and endothermic chemisorption process. Wang *et al.*, [69] employed MAC as an adsorbent and as a catalyst for the Fenton-like degradation of MO, achieving up to 95% removal efficiency with simultaneous in-situ regeneration through sodium persulfate activation. The study revealed that degradation efficiency increased with temperature, underscoring the thermally favored nature of the process. Prusov *et al.*, [73] further supported the effectiveness of chemical activation using $FeCl_3$ for preparing cellulose-derived magnetic carbon composites, which demonstrated significant adsorption capacities for MB and MO due to the high degree of graphitization achieved during synthesis.

Furthermore, the choice of raw material and synthesis conditions plays a crucial role in determining the efficiency of the final adsorbent. Alam *et al*., [67] fabricated MAC from corn-cob biomass, optimizing parameters such as adsorbent dosage and contact time to enhance the removal of Acid Orange 8 and Acid Red 4. Thermodynamic analysis confirmed that the adsorption was endothermic and spontaneous at elevated temperatures, with entropy changes suggesting increased randomness at the solid-solution interface. Mouhamed *et al*., [70] utilized sawdust-derived activated carbon magnetized with Fe_3O_4 for Crystal Violet (CV) removal, achieving 100% removal efficiency under optimized conditions and confirming the nanocomposite's effectiveness through pseudo-second-order kinetics. These findings highlight the potential of using diverse agricultural and industrial waste as sustainable sources for fabricating magnetic adsorbents with high dye removal capacities.

Regeneration and reusability of the adsorbents also emerged as critical factors in evaluating their practical applicability. Alam *et al*., [67] demonstrated that their corn-cob-based magnetic adsorbent retained up to 76% efficiency after five adsorption-desorption cycles, illustrating good recyclability. Similarly, Wang *et al*., [69] reported that the MAC maintained above 90% MO removal efficiency after five regeneration cycles via Fenton-like degradation, emphasizing the durability and practicality of the synthesized materials for long-term wastewater treatment applications. Such evidence suggests the feasibility of MAC in large-scale environmental remediation efforts, provided that their structural integrity and surface functionalities are preserved during repeated use.

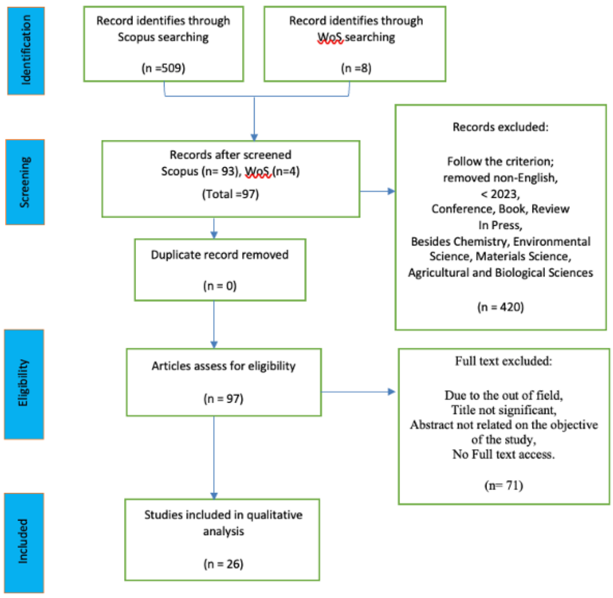

Fig. 1. Flow diagram of the proposed searching study [81]

In summary, the reviewed studies collectively demonstrate that the synthesis of magnetic nanocomposites from various biomass sources or commercial activated carbon through functionalization and magnetic incorporation significantly enhances dye adsorption capabilities. Optimized synthesis conditions and functionalization strategies, such as chemical activation, surface modification, and coupling with catalytic degradation processes, are pivotal to achieving high removal efficiencies. The consistent observation of spontaneous, endothermic, and chemisorption-dominated adsorption processes further confirms the effectiveness of these advanced materials for treating dye-contaminated wastewater.

3.2 Theme 2: Adsorption and Removal of Dyes

The development of magnetic and activated carbon-based adsorbents for removing dyes from wastewater has been extensively explored, demonstrating significant improvements in adsorption capacity, reusability, and ease of separation. Bouider and Rida [58] synthesized a MAC capable of removing MO, RhB, and phenol, achieving maximum monolayer adsorption capacities of 218, 135, and 101 mg/g, respectively, with stability exceeding 80% removal efficiency after multiple cycles. Similarly, Salama *et al*., [59] enhanced the surface area and porosity of magnetic carbonaceous materials derived from waste plastics, reporting MB adsorption efficiencies of 96.3% for graphene and slightly lower for carbon spheres and nanotubes. Kochito *et al*., [61] further confirmed the high performance of magnetic biochar nanocomposites from coffee husk and khat waste, where Fe_3O_4-loaded biochar achieved removal efficiencies above 99% for MB. These findings collectively underscore the potential of magnetically modified carbonaceous materials for effective dye remediation in aqueous environments.

Moreover, optimization studies have revealed the significance of parameters such as pH, contact time, and adsorbent dose in improving adsorption performance. Anitha *et al*., [64] utilized walnut shell-derived magnetic activated carbon composites (MWNSC), demonstrating maximum adsorption capacities of 303.30 mg/g for MO and 345.70 mg/g for MB, fitting well with the Langmuir isotherm model and following pseudo-second-order kinetics. Meanwhile, Liang *et al*., [65] produced in-situ MAC from sludge, straw, and steel slag, achieving a removal efficiency exceeding 95% for MB under favorable conditions, highlighting the multilayer physisorption mechanism involving intraparticle diffusion and chemisorption. Similarly, Rajendran *et al*., [66] prepared MAC from watermelon shell (MWMSC), achieving adsorption capacities of 303.30 mg/g for MB and 345.70 mg/g for MO, through spontaneous and exothermic adsorption processes. These studies highlight the consistent application of the Langmuir isotherm and pseudo-second-order kinetics models across various magnetically enhanced biochars and carbons.

Incorporating advanced activation methods such as Microwave-Induced Reaction Systems (MIRS) has further advanced the field. Li *et al*., [62] synthesized Fe_3O_4@C composites capable of achieving a high MB adsorption capacity of 305.0 mg/g, maintaining stable performance even after 16 regeneration cycles. Regeneration was facilitated without the use of external oxidizing agents, demonstrating high reusability and maintaining structural integrity, as confirmed by SEM and Fourier transform infrared spectroscopy (FTIR) analyses. In a similar vein, Karuppaiyan *et al*., [68] used thermally activated metakaolin (AK) for MB removal, achieving a removal capacity of 97.8 mg/g. They reported chemisorption as the primary mechanism, which was confirmed by X-ray photoelectron spectroscopy (XPS) analysis, illustrating ionic interactions between MB and the activated kaolinite surface. These studies suggest that surface functionalization and innovative synthesis approaches significantly enhance dye adsorption efficiency and prolong the longevity of the adsorbent.

Notably, recent works have emphasized the creation of adsorbents with exceptionally high surface areas and magnetic properties to facilitate easy recovery and high dye uptake. Wang *et al*., [71] introduced Magnetic Asphalt-based Activated Carbon (MAAC) with an extraordinarily high surface area of 2880 m^2/g and pore volume of 1.809 cm^3/g. The material demonstrated a maximum MB adsorption capacity of 710 mg/g and maintained over 66% of its initial capacity after five regeneration cycles. This performance, superior to many conventional adsorbents, was attributed to the synergistic effects of microporosity, abundant oxygen functional groups, and embedded zerovalent iron. Such findings reinforce the advantages of designing porous magnetic materials for large-scale wastewater treatment applications.

Overall, the reviewed studies consistently demonstrate that magnetic activation, chemical modification, and surface functionalization are effective strategies for enhancing the adsorption capacities and recyclability of adsorbents for dye removal from wastewater. Future research could further explore sustainable raw materials, optimize synthesis conditions, and develop low-cost regeneration methods to facilitate the commercial application of these promising materials.

3.3 Theme 3: Environmental and Sustainable Applications

The application of magnetic biochar composites and activated carbon-based materials has demonstrated significant effectiveness in treating dye-contaminated wastewater, aligning with the environmental and sustainable application theme. A considerable number of studies have focused on enhancing the removal efficiency of dyes by modifying biochar with magnetic properties or combining it with metal oxides and other supporting materials. For instance, Tomin and Yazdani [56] demonstrated that chemically activated Bio-based Activated Carbons (BACs), such as BAC-Fe, BAC-Cu, and BAC-Na, exhibited superior adsorption capacities for organic pollutants, achieving up to 97% removal efficiency. Similarly, Balci *et al*., [72] explored a hybrid process combining Magnetite with Activated Sludge (M/AS), which significantly increased dye removal efficiency, reaching up to 99.5% for Reactive Red 195. Meanwhile, Gogoi *et al*., [74] developed a Fe_3O_4-biochar composite that successfully degraded 89.3% of Fast Green dye through Fenton-like reactions, highlighting the synergistic effect of magnetite and biochar in catalyzing advanced oxidation processes.

Furthermore, the integration of magnetically modified adsorbents into biological treatment systems has also gained attention due to their combined physical and biological mechanisms for pollutant removal. Dao *et al*., [76] synthesized MAC from Litsea glutinosa seeds and reported enhanced removal efficiencies for both MB and nickel (II) ions when MAC was integrated into an activated sludge system. Similarly, Nawaz *et al*., [75] utilized acid-activated Dalbergia Sissoo leaf powder and its Magnetic Nanocomposite (DSMNC) to remove alizarin red S dye, achieving removal efficiencies of 76.63% and 97.89%, respectively, under optimal conditions. The findings collectively emphasize that magnetically enhanced systems offer improved adsorption capacities, facilitate faster pollutant removal, and promote better sludge settling properties compared to traditional methods [76], [75], and [72].

Research efforts have also explored the structural design of magnetic adsorbents to maximize efficiency and reusability. Ali *et al*., [77] engineered a magnetic bio-based adsorbent utilizing H_2O_2-activated zeolite and turmeric carbohydrate polymer, demonstrating high maximum capacities (268.67–307.73 mg/g) for MB adsorption and multi-molecular adsorption mechanisms. Likewise, Chaharkam *et al*., [79] compared powder, film, and granule forms of MAC derived from Oleaster seeds for MB removal, finding that the powdered form exhibited the highest adsorption capacity (68.49 mg/g). Safe *et al*., [78] provided additional insights by demonstrating that MAC composites can achieve rapid removal of imidacloprid in only 10 minutes, underscoring the benefits of magnetic property enhancement for fast and efficient adsorption processes. These studies collectively suggest that morphology, surface functionalization, and magnetization have a significant influence on adsorption dynamics, particularly in wastewater treatment applications.

Moreover, combining different sorbent materials into composite systems has been demonstrated to enhance performance for both heavy metal removal and dye adsorption. Liu *et al*., [80] fabricated nanomagnetic aerogels by incorporating bentonite and activated carbon into alginate-based magnetic beads, achieving high efficiency for cadmium removal from aqueous solutions. The adsorption data fitting to the Langmuir isotherm and pseudo-second-order kinetic models suggested that chemical adsorption dominated the process, consistent with findings reported by Nawaz *et al*., [75] and Ali *et al*., [77]. The thermodynamic parameters obtained in these studies confirmed that the adsorption processes were spontaneous and predominantly exothermic, reinforcing the roles of physical and chemical mechanisms, such as hydrogen bonding, electrostatic forces, and π–π interactions in pollutant capture.

Collectively, the reviewed literature highlights the significant advancements in developing magnetically activated biochar and carbon composites for sustainable environmental applications. The findings consistently demonstrate that incorporating magnetic properties enhances pollutant removal efficiency and facilitates material recovery and reuse, addressing critical challenges in wastewater treatment. Advanced modeling and kinetic studies have significantly enhanced the understanding of adsorption mechanisms, informing the design of next-generation adsorbents for broader environmental remediation efforts.

4. Discussion

This comprehensive review elucidates three dominant themes that shape recent research on ANBCs for dye adsorption. First, the synthesis and characterization of magnetic nanocomposites (Theme 1) emerged as a central focus, with a clear trend toward optimizing activation methods and integrating magnetic nanoparticles to maximize structural and functional performance. Studies such as those by Li *et al*., [55] and Nguyen *et al*., [57] highlighted the impact of carefully tailored protocols. Specifically, the use of chemical activators like K_2CO_3 and $FeCl_3$ yielded exceptionally high surface areas (e.g., 2880 m^2/g as reported by Wang *et al*., [71]) and favorable pore architectures, leading directly to enhanced adsorption capacities. A notable and encouraging trend was the increasing use of agricultural and industrial waste feedstocks, such as corn cob, palm kernel shells, and waste plastics, reflecting a growing commitment to sustainability and circular economy principles. However, inconsistencies across activation protocols and magnetic nanoparticle loading ratios introduced significant variability in material performance, highlighting an urgent need for standardization to ensure reproducibility and scalability. Theme 2 emphasized the adsorption mechanisms of ANBCs, revealing that chemisorption, driven by electrostatic interactions, hydrogen bonding, and π-π stacking, dominated pollutant removal processes, as evidenced by high removal efficiencies (>90%) and pseudo-second-order kinetic behavior. Furthermore, the adoption of hybrid systems that combine adsorption with Fenton-like degradation or photocatalytic processes has emerged as a promising but underexplored frontier. Finally, Theme 3 underscored the growing interest in the environmental applications of ANBCs, particularly their regenerative potential and integration into biological wastewater treatment systems. Encouragingly, regeneration studies have depicted that many ANBCs maintain a removal efficiency of over 70% across multiple cycles, although the sustainability of energy-intensive regeneration methods remains a critical concern. Collectively, these findings position ANBCs as a versatile and scalable solution for wastewater remediation, while simultaneously revealing key technical and operational challenges that must be addressed to translate laboratory successes into real-world impacts.

The interpretation of these findings provides deeper insight into why each theme was selected and its broader significance for the field. The focus on synthesis and characterization (Theme 1) was prioritized because material properties—such as surface area, pore volume, and magnetic behavior—are fundamental determinants of adsorption performance. The recurrence of chemical activation methods and the choice of magnetic nanoparticles reflect a deliberate effort by researchers to optimize these parameters for practical applications. On the contrary, the observed variability across studies underscores a broader trend in materials science: the tension between innovation and standardization. Without common benchmarks for activation conditions and magnetic loading, meaningful comparisons and large-scale adoption remain difficult. Theme 2, centered on adsorption mechanisms, revealed the robustness of chemisorption processes and the dominance of monolayer adsorption models, suggesting that ANBCs interact predictably with target pollutants under controlled conditions. Nevertheless, the current focus on single-dyed systems limits the applicability of findings to real-world wastewater, which typically contains complex mixtures of dyes and other contaminants. Hybrid systems that combine adsorption with catalytic degradation offer an exciting avenue to overcome these limitations, although further research is needed to realize their potential fully. Theme 3 highlighted the environmental and sustainable aspects of the ANBC application, revealing its compatibility with biological treatment systems and its potential for reuse. Conversely, the energy demands associated with thermal and chemical regeneration processes raise questions about the true sustainability of these materials over extended use cycles. Thus, while the field has made significant strides in advancing ANBC development, it must now pivot toward addressing these gaps—particularly in terms of scalability, sustainability, and performance in complex effluent environments—to fulfill its promise in industrial applications.

The implications of these findings for practice are substantial, particularly for industries such as textiles, leather, and paper manufacturing, where dye-laden wastewater presents serious environmental and regulatory challenges. The use of ANBCs derived from waste feedstock offers a dual benefit: mitigating pollution from both solid waste and wastewater streams, thereby aligning principles of sustainable resource management. Policymakers could facilitate the adoption of ANBC technologies by providing incentives for green innovations or by tightening regulations on industrial dye discharge, hence creating a market pull for sustainable treatment options. From a technical standpoint, standardizing synthesis protocols—such as optimizing Fe_3O_4 loading to prevent pore blockage without compromising surface area—and developing low-energy regeneration methods (e.g., UV-assisted or biologically-based approaches) are critical next steps. Moreover, pilot-scale trials in real-world wastewater environments, accounting for variables such as competing ions, organic load, and salinity, are essential to validate laboratory findings under operational conditions. Future research should prioritize the development of multifunctional ANBCs capable of simultaneously removing multiple classes of pollutants, such as cationic and anionic dyes, heavy metals, and organic compounds, reflecting the complexity of actual industrial effluents. Strategies such as co-doping with photocatalytic oxides (e.g., TiO_2) or integrating biopolymers (e.g., alginate) can enhance material stability and broaden its functional capabilities. Additionally, green activation techniques—such as steam activation or microwave-assisted synthesis—and the use of non-toxic magnetic precursors should be explored to minimize the environmental footprint further. Life Cycle Assessments (LCAs) and toxicity studies of ANBCs are also urgently needed to ensure that these materials deliver net environmental benefits throughout their entire life cycle, from production to use and disposal. Although insightful, this study had several limitations, including a narrow publication window (2023–2025), language restrictions, and a relatively small sample size (n=26), which may limit the generalizability of its conclusions. Future systematic reviews should expand database coverage, include grey literature, and incorporate industrial cost-benefit analyses to better inform real-world applicability. Despite these limitations, this review contributes a critical synthesis of emerging trends and challenges in ANBC research, providing a roadmap for scholars and practitioners committed to advancing sustainable wastewater treatment technologies.

5. Conclusion

This systematic review consolidates advancements in ANBC for dye adsorption across synthesis, performance, and application domains. Chemical activation and magnetic nanoparticle integration emerge as the primary strategies for enhancing adsorption capacity, while agricultural and industrial waste feedstocks offer alignment with circular economy principles. However, variability in synthesis protocols across studies highlights the need for methodological standardization. Regeneration remains a critical factor for practical deployment. Although ANBCs demonstrate reusability across multiple cycles, the energy demands of current regeneration methods constrain scalability. Environmental compatibility with biological treatment systems appears favorable, yet validation under complex, real-world effluent conditions is lacking. Future research should prioritize three directions: development of multifunctional ANBCs capable of addressing mixed pollutant streams, advancement of green synthesis techniques, and integration of life cycle assessments to evaluate holistic sustainability. This review's scope is limited by its focus on recent publications and English-language sources. Nevertheless, the consolidated evidence supports ANBC as a viable direction for industrial wastewater treatment, contingent on interdisciplinary efforts to translate laboratory-scale findings into field applications.

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