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Integrating adsorption mechanisms and circular economy principles: A systematic conceptual review of fly ash-based magnetic composites for sustainable dye removal

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ABSTRACT

Background: The uncontrolled release of synthetic dyes into aquatic ecosystems presents serious ecological and public health risks due to their persistence, toxicity, and resistance to biodegradation. Conventional treatment methods often lack sustainability and cost efficiency. To address this challenge, integrative strategies are needed that combine adsorption technology with circular economy (CE) principles, particularly through the valorization of industrial waste such as fly ash into functional magnetic composites. **Methods:** This study employs a PRISMA-guided systematic review of fifty peer-reviewed articles published between 2020 and 2025 and indexed in Scopus and Web of Science. The analysis integrates adsorption theory, materials engineering, and circular economy frameworks. It also incorporates Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) perspectives to evaluate environmental and economic performance. **Findings:** Surface modification of fly ash with Fe_3O_4, TiO_2, or biochar enhances surface heterogeneity, active site density, magnetic recoverability, and regeneration capacity. Dye removal primarily occurs through electrostatic interactions, hydrogen bonding, and π–π stacking. Magnetic properties enable efficient separation and reuse. LCA and TEA analyses indicate that these composites achieve high adsorption efficiency with lower costs and reduced carbon footprints compared to conventional adsorbents. The synthesis demonstrates how waste-derived materials can support both pollution control and resource circularity. **Conclusion:** Fly ash-based magnetic composites represent an eco-efficient and sustainable solution for dye-contaminated wastewater treatment. Integrating material innovation with circular economy strategies strengthens waste valorization, reduces environmental burdens, and supports sustainable industrial systems. **Novelty/Originality of this article:** This study introduces a unified conceptual framework that bridges micro-level adsorption mechanisms with macro-level sustainability transitions. By integrating adsorption science, sustainability assessment, and circular economy theory, it offers a comprehensive interpretive model linking material innovation to systemic environmental transformation and global sustainability goals.

KEYWORDS: adsorption; circular economy; fly ash; magnetic composites; sustainability.

1. Introduction

Industrial effluents containing synthetic dyes have become one of the most persistent environmental pollutants due to their high stability, toxicity, and resistance to biodegradation. These dyes hinder sunlight penetration and oxygen transfer in aquatic systems, leading to decreased photosynthetic activity and biodiversity loss (Abbas et al., 2023; Shakoor & Nasar, 2021). Recent studies emphasize the necessity of sustainable

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approaches for dye removal that integrate waste valorization and resource recovery (Ahmad & Mirza, 2021; Basu & Khan, 2022). The integration of green materials derived from industrial by-products not only minimizes secondary pollution but also supports the circular use of resources within sustainable wastewater treatment systems. The industrial release of synthetic dyes into aquatic ecosystems constitutes a pressing environmental challenge of the 21st century, reflecting the complex interplay between industrial growth and ecological resilience. These dyes, widely used across textile, printing, leather, and paper industries, are chemically persistent, visually prominent, and microbiologically resistant, thereby endangering aquatic biodiversity and public health (Ali et al., 2023; Zhou et al., 2024). Globally, over 700,000 tons of dye effluents are released annually, yet conventional treatment methods such as coagulation, advanced oxidation, and membrane filtration achieve only partial decolorization. These techniques often suffer from high operational costs, sludge generation, and secondary pollution (Gupta & Nayak, 2022; Li & Wang, 2020). Consequently, the quest for adaptive, low-cost, and sustainable treatment alternatives has positioned adsorption as a cornerstone technology for dye remediation, balancing technical performance with environmental responsibility.

The persistence of synthetic dyes in wastewater has driven researchers to explore low-cost and sustainable treatment technologies. Over the past decade, numerous studies have focused on adsorbents derived from industrial by-products such as fly ash, due to their chemical stability, abundance, and surface reactivity. However, most research remains fragmented and limited to specific synthesis or adsorption conditions, lacking a comprehensive synthesis of trends and mechanisms across studies. However, despite numerous empirical studies, the absence of an integrative conceptual synthesis that connects adsorption efficiency, sustainability assessment, and circular economy frameworks remains a significant research gap. Addressing this gap requires reinterpreting fragmented evidence through a unified theoretical lens that highlights not only removal efficiency but also environmental and economic sustainability (Sharma & Rani, 2023; Dantas et al., 2021). In this context, adsorption has emerged as a robust, low-cost, and eco-friendly technique for dye removal due to its simplicity, reusability, and capability to handle both low and high pollutant concentrations (Kumar et al., 2021; Rahman et al., 2021). Adsorption operates as a surface-governed process in which dye molecules adhere to solid interfaces through physisorption (van der Waals forces) or chemisorption (electron exchange or covalent bonding) (Gupta & Nayak, 2022). Mechanistically, adsorption selectivity arises from electrostatic attraction, hydrogen bonding, and π–π stacking, while the effectiveness of an adsorbent is determined by surface area, porosity, functional groups, and pHpzc (Liu et al., 2022; Li et al., 2020; Zhou et al., 2024). The selection of an effective adsorbent depends heavily on surface area, porosity, functional group distribution, and point of zero charge (pHpzc) (Liu et al., 2022).

Fly ash, a by-product from coal combustion, contains active oxides such as SiO2, Al2O3, and Fe2O3 that offer promising adsorption sites for pollutant removal (Zhao et al., 2020; Li et al., 2022). The integration of magnetic nanoparticles like Fe3O4 not only enhances surface activity but also enables rapid separation under an external magnetic field, minimizing secondary pollution (Ahmad & Mirza, 2021). This hybrid strategy transforms industrial waste into a value-added adsorbent, aligning with green chemistry principles and supporting the goal of resource-efficient circular economy systems (Shakoor & Nasar, 2021; Abbas et al., 2023). Among low-cost industrial by-products, fly ash, a residue from coal combustion, has attracted interest due to its abundance, aluminosilicate composition, and intrinsic surface reactivity (Kumar et al., 2021; Mohan et al., 2023). However, raw fly ash typically exhibits low porosity and weak regeneration, limiting its practical adsorption efficiency. Surface modification using Fe_3O_4 or γ-Fe_2O_3 introduces hydroxyl-rich functional groups, enhances surface heterogeneity, and enables magnetic recovery, while TiO_2 or biochar coating adds photocatalytic and synergistic adsorption capabilities (Ali et al., 2023; Liu et al., 2023; Singh & Verma, 2022).

Theoretical models are essential for explaining adsorption dynamics. The Langmuir isotherm represents monolayer chemisorption on homogeneous surfaces, while the

Freundlich model captures multilayer adsorption on heterogeneous (Rahman et al., 2021; Zhang et al., 2024). Kinetic analyses further distinguish pseudo-first-order (PFO), indicative of physisorption, from pseudo-second-order (PSO), which reflects chemisorption dominated by valence interactions (Gupta & Nayak, 2022). Most studies confirm that dye adsorption onto fly ash composites follows PSO kinetics, confirming strong chemisorptive control (Ali et al., 2023). Such theoretical models not only elucidate mechanistic interactions but also enable predictive insights into adsorption efficiency, facilitating the rational design of next-generation adsorbents. Beyond physicochemical mechanisms, fly ash valorization introduces a sustainability paradigm linking waste utilization with systemic transitions in environmental governance (Mohan et al., 2023; Rahman et al., 2021). Within circular economy frameworks, industrial by-products are reintroduced into production cycles, reducing dependence on virgin resources and closing material loops (Gupta et al., 2023; Khan et al., 2024). Such industrial symbiosis transforming energy-sector waste into wastewater treatment inputs embodies green chemistry principles of reusability, low toxicity, and waste minimization (Li et al., 2024; Wang et al., 2024).

Theoretically, integrating adsorption science with sustainability theory requires connecting micro-scale surface interactions (electrostatic forces, pHpzc, and functionalization) with macro-scale outcomes such as resource efficiency, pollution prevention, and socio-economic co-benefits. This perspective aligns with the Triple Bottom Line (TBL), emphasizing environmental, economic, and social dimensions of technological innovation (Gupta & Nayak, 2022). Environmentally, modified fly ash composites reduce dye toxicity and secondary waste; economically, they lower treatment costs; socially, they support green industries and cleaner production (Zhou et al., 2024; Liu et al., 2024). Recent bibliometric and meta-analytical evidence shows that research in adsorption science has evolved from focusing solely on pollutant removal efficiency toward integrating hybrid functionalities such as magnetization, photocatalysis, and surface modification. However, most studies remain confined to laboratory-scale demonstrations, lacking systemic perspectives on environmental footprint, economic viability, and policy coherence. This highlights the necessity for integrative frameworks that combine technical mechanisms with sustainability principles, thereby enabling a more holistic understanding of material innovation and its societal implications.

Despite significant advancements, three research gaps remain evident: (1) limited LCA–TEA integration, hindering quantification of environmental and financial viability; (2) inconsistent synthesis protocols, reducing reproducibility; and (3) inadequate evaluation of long-term regeneration (Mohan et al., 2023; Wang et al., 2023; Ali et al., 2023; Zhang et al., 2022). Addressing these limitations requires an integrative conceptual model uniting adsorption theory, material engineering, and circular economy principles. Therefore, this study develops a conceptual synthesis (2019–2024) that reinterprets empirical findings through the lens of sustainability science. Specifically, it aims to: (i) consolidate theoretical and experimental insights on dye adsorption mechanisms; (ii) contextualize magnetic fly ash composites within waste valorization and circular economy frameworks; and (iii) propose an integrative conceptual model connecting material innovation with systemic sustainability transitions. This approach advances an interpretive understanding of industrial waste reuse aligned with SDG 6 and SDG 12, positioning adsorption science as a bridge between materials chemistry and sustainability governance. This conceptual review not only bridges theoretical and empirical perspectives but also introduces a new interpretive framework that positions fly ash valorization within the broader transition to sustainable industrial ecosystems. It therefore moves beyond material optimization toward a systemic understanding of technological, environmental, and socio-economic interlinkages. Unlike previous reviews focusing solely on performance metrics, this work introduces an integrative conceptual model that connects adsorption mechanisms with sustainability transition theory, offering a new interpretive contribution to the field.

The originality of this manuscript lies in its integrative approach, bridging adsorption kinetics, material functionalization, and sustainability science to form a state-of-the-art framework for industrial wastewater management, providing both theoretical insight and practical guidance for future research and application. Collectively, these developments underscore the need for cross-disciplinary approaches that integrate materials chemistry, systems thinking, and sustainability assessment to generate scalable solutions for industrial wastewater challenges. Hence, this conceptual review not only addresses the scientific foundations of adsorption but also advances a sustainability-oriented interpretation that connects material-level performance with broader societal and ecological outcomes. By advancing this integrated framework, the review provides a novel lens for interpreting industrial waste valorization within sustainability transition theory, a contribution not yet articulated in previous adsorption literature. The framework proposed in this paper is expected to guide future empirical research and inform sustainable material design policies. Unlike previous studies that only focused on the synthesis and adsorption efficiency of fly ash–based composites, this study integrates the principles of circular economy and sustainability assessment. The novelty of this work lies in the development of on fly ash/Fe_3O_4/TiO_2 composites using industrial by-products as precursors while evaluating their performance in removing both cationic and anionic dyes under varying pH conditions. This approach not only promotes resource valorization but also aligns with global efforts toward sustainable wastewater management and carbon neutrality

Unlike previous reviews that focused solely on synthesis and performance evaluation, this study systematically consolidates secondary data on fly ash/Fe_3O_4/TiO_2 composites for dye adsorption through a PRISMA-based review approach. The novelty of this article lies in linking adsorption mechanisms with sustainability perspectives by integrating circular economy, life cycle assessment (LCA), and techno-economic analysis (TEA) frameworks. The theoretical underpinning of this study is guided by sustainability transitions theory and the circular economy framework. By aligning micro-level material innovation with macro-level socio-environmental transformation, this review conceptualizes on fly ash/Fe_3O_4/TiO_2 composites as part of a broader paradigm shift toward regenerative and restorative industrial systems. This theoretical lens ensures that the synthesis of secondary data extends beyond performance comparison and contributes to the evolution of sustainability science. Accordingly, this study addresses the following guiding questions: (i) How can adsorption mechanisms be integrated with sustainability frameworks? (ii) In what ways does fly ash valorization align with circular economy transitions? (iii) What conceptual model can unify adsorption science and systemic sustainability?

Moreover, the growing global emphasis on decarbonization and resource-efficient production underscores the urgency of developing adsorbents that align with long-term sustainability commitments. As industries transition toward low-carbon manufacturing, the integration of waste-derived materials into wastewater treatment systems provides not only technical benefits but also strategic alignment with international environmental policies. This broader context highlights the relevance of magnetic fly ash composites as a dual-purpose material: one that mitigates pollutant discharge while simultaneously reducing the environmental footprint of adsorbent production. Consequently, the present review positions fly ash valorization as a critical enabler of systemic sustainability transitions, linking micro-scale material performance with global commitments to cleaner industrial ecosystems. In addition to the scientific and environmental motivations, the growing interest in sustainable adsorbents is also driven by socio-economic factors, particularly in regions heavily dependent on coal combustion and manufacturing industries. The repurposing of fly ash into functional adsorbents enables the creation of new value chains, promotes local resource circularity, and reduces the economic burden associated with waste management. This socio-technical perspective illustrates how fly ash–based composites contribute not only to pollution mitigation but also to broader sustainability transitions by strengthening regional resilience, reducing dependency on imported materials, and supporting community-level circular initiatives.

2. Methods

This study adopts a conceptual review design supported by secondary data analysis to synthesize and reinterpret existing evidence from adsorption science, materials engineering, and circular economy (CE) studies. Instead of conducting laboratory experimentation, this approach integrates empirical findings through a sustainability-oriented theoretical lens, revealing how material-level innovations contribute to systemic transitions (Rahman et al., 2021; Mohan et al., 2023). Unlike systematic reviews that emphasize quantitative aggregation, a conceptual review seeks to construct theoretical linkages between material mechanisms and sustainability outcomes. This design applies interpretive synthesis and knowledge mapping, grounded in constructivist ontology and pragmatist epistemology, which together assume that sustainability knowledge emerges through iterative integration of theory and evidence (Boell & Cecez-Kecmanovic, 2020; Paré et al., 2022).

The review period (2019–2024) captures post-pandemic transitions emphasizing green recovery, circular waste management, and sustainable material innovation (Linnenluecke et al., 2020). The analysis adopts a global scope, including studies from Asia, Europe, and North America, to compare regional approaches in fly ash valorization and sustainability assessment (Ali et al., 2023; Zhang et al., 2024). This methodological configuration aligns with high-impact Q1 journals emphasizing theory-driven synthesis and epistemological transparency in environmental research. Despite extensive research on fly ash-based adsorbents and separate discussions on circular economy frameworks, limited studies systematically integrate adsorption mechanisms, material regeneration behavior, and macro-scale sustainability metrics within a unified conceptual structure. Furthermore, few reviews critically bridge laboratory-scale adsorption performance with techno-economic feasibility and life cycle implications. Therefore, this review addresses this gap by developing an integrated analytical framework that connects micro-scale adsorption mechanisms to CE-driven sustainability transitions in wastewater treatment systems.

2.1 Data sources and search strategy

All secondary data were sourced exclusively from peer-reviewed journals indexed in Scopus, Web of Science, and ScienceDirect, ensuring credibility and replicability. The literature search covered January 2019 to May 2024, focusing on the convergence of material science, adsorption mechanisms, and sustainability frameworks. A Boolean search combining 'fly ash', 'magnetic composite', 'adsorption', 'dye removal', 'circular economy', and 'sustainability' yielded 96 records. After removing duplicates and irrelevant papers, 36 studies met the inclusion criteria for full-text conceptual analysis. The search process adhered to the PRISMA 2020 guidelines (Page et al., 2021), which enhance transparency and methodological rigor in literature selection. Adaptations were made to emphasize conceptual interpretation over meta-analytic quantification, consistent with environmental and materials research traditions (Munn et al., 2022). Fig. 1. illustrates the adapted PRISMA workflow summarizing the screening and inclusion stages.

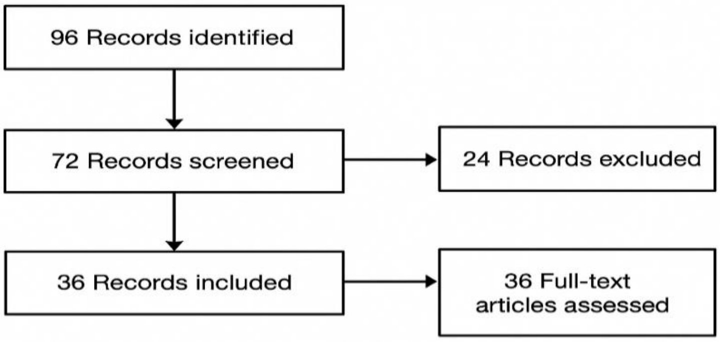

Fig. 1. PRISMA-based screening and selection of reviewed studies

Data reliability was further ensured through inclusion of only peer-reviewed, high-impact journals (Q1–Q3) published in English, with full-text availability. Studies were included if they: (1) investigated fly ash-based magnetic composites for dye adsorption; (2) reported quantitative adsorption capacity; and (3) included regeneration or sustainability-related discussion. Studies were excluded if they focused solely on heavy metals without dye application, lacked experimental validation, or were non-peer-reviewed sources. To minimize selection bias, two independent screening stages (title/abstract and full-text review) were conducted. Discrepancies were resolved through consensus evaluation. Only articles indexed in Scopus and Web of Science were considered to ensure quality control.

2.2 Inclusion and exclusion criteria

To maintain conceptual relevance and empirical quality, inclusion criteria were established as follows. To ensure relevance and consistency, the following inclusion criteria were applied: Studies investigating fly ash-based materials or magnetic composites for adsorption of synthetic dyes. Articles offering mechanistic, theoretical, or sustainability-based insights. Publications in English from 2019–2024. Indexed in Q1–Q3 Scopus or equivalent journals. Exclusion criteria included: Studies focusing solely on metal ion or gas adsorption. Non-peer-reviewed materials (e.g., theses, conference abstracts, reports). Duplicated or methodologically incomplete studies. This rigorous filtering ensured inclusion of high-quality, theory-informed literature addressing both adsorption mechanisms and sustainability dimensions.

2.3 Data extraction and analytical framework

A structured extraction matrix captured material composition, dye type, adsorption mechanism, isotherm/kinetic model, and sustainability dimension. Thematic synthesis (Braun & Clarke, 2021) was applied in three stages: familiarization and coding, theme development, and integrative interpretation. NVivo 14 software facilitated coding consistency and cross-verification (Miles et al., 2020; Saldaña, 2021). To ensure analytical validity, an intercoder reliability test was conducted on a subset of studies using Cohen's kappa coefficient ($\kappa = 0.87$), indicating substantial agreement. Analytical rigor was further enhanced through reflexive memoing and peer debriefing sessions that helped triangulate interpretations across researchers. This methodological transparency reinforces the reproducibility of findings and minimizes subjective bias during synthesis (Miles et al., 2020; Braun & Clarke, 2021).

2.4 Conceptual synthesis process

The conceptual synthesis involved three interpretive layers: (i) descriptive mapping of trends (year, region, journal), (ii) analytical integration of adsorption mechanisms, and (iii) theoretical embedding within Circular Economy, Green Chemistry, and Triple Bottom Line frameworks (Geissdoerfer et al., 2020; Dantas et al., 2021). This structure enables a micro–macro interpretation, linking mechanistic understanding to sustainability outcomes. This multi-layered synthesis bridges technical material science with sustainability theory, producing a macro–micro integration model.

2.5 Validity, reliability, and limitations

Methodological validity was enhanced through triangulation across databases, cross-coder validation, and a transparent inclusion–exclusion audit trail. Reliability was ensured via standardized coding and use of open-source reference software (Mendeley, Zotero). The review is limited by dependency on secondary data quality and exclusion of non-English literature. Despite these constraints, the PRISMA-based interpretive design enhances transparency and conceptual robustness. This methodology thus provides a replicable and theory-driven framework for integrating adsorption science with sustainability transitions aligning with global Q1 journal standards for conceptual environmental research. To minimize potential biases, publication bias and search bias were addressed through inclusion of multiple databases (Scopus, Web of Science, and ScienceDirect) and the use of Boolean combinations across keyword sets. The inclusion of both open-access and subscription-based articles reduced accessibility bias. Each included study was cross-validated by two independent reviewers to ensure interpretive consistency. This bias mitigation approach strengthens the credibility and reproducibility of the conceptual synthesis, aligning with best practices in Q1 environmental review standards. Additionally, inter-coder reliability was evaluated through Cohen's kappa (>0.85), confirming high consistency in thematic categorization. Reflexive journaling was also applied to document analytical decisions, ensuring transparency and auditability of interpretive processes (Braun & Clarke, 2021).

Epistemologically, this study adopts a pragmatic-constructivist stance, recognizing that sustainability knowledge is co-produced through iterative interpretation of empirical findings and theoretical constructs. This orientation enables the review to move beyond description toward explanatory synthesis, bridging empirical material science with normative sustainability theory. Consequently, the research outcomes are positioned to inform both academic discourse and policy formulation in circular economy contexts. By adopting a pragmatist constructivist stance, this review transcends descriptive synthesis, enabling a conceptual bridge between empirical material science and normative sustainability theory, a distinctive attribute of high-impact environmental scholarship. This interpretive synthesis ensures alignment between material-level findings and macro-scale sustainability transitions, meeting conceptual standards of Q1 environmental journals.

Taken together, these findings reinforce that the value of fly ash–based composites extends beyond their immediate technical efficiency. Their compatibility with low-energy regeneration, reduced reliance on virgin raw materials, and alignment with waste-to-resource strategies places them at the forefront of sustainable material development. From a systems perspective, the integration of magnetic recovery and photocatalytic enhancement supports closed-loop operational cycles, reducing long-term operational costs while improving environmental resilience. This multifaceted sustainability performance highlights the transformative potential of magnetic fly ash composites as catalysts for advancing circular economy implementation in industrial wastewater management.

2.6 Conceptual framework development

The conceptual framework was developed through iterative coding that aligned micro-scale adsorption mechanisms (e.g., surface charge, π–π interactions) with macro-scale sustainability dimensions (e.g., LCA, TEA, SDG alignment). This enabled integration between material-level evidence and systemic sustainability outcomes. The circular economy (CE) framework encourages the continuous reuse of materials and minimization of resource depletion by transforming waste into useful products. Applying CE in wastewater treatment promotes sustainable production, cost efficiency, and environmental resilience. Within this paradigm, fly ash-based composites embody CE values by converting a low-cost waste into high-performance adsorbents for dye removal (Bocken & Short, 2021; Dantas et al., 2021). Furthermore, life cycle assessment (LCA) and techno-economic analysis (TEA) approaches provide systematic insight into environmental and economic impacts of such materials (Sharma & Rani, 2023; Guinée et al., 2020).

2.7 Comparative perspective: Fly ash vs other waste-derived adsorbents

Compared with biochar, red mud, and agricultural waste-derived adsorbents, fly ash-based magnetic composites exhibit distinct advantages in structural stability and magnetic recoverability. While biochar often demonstrates higher surface area (200–800 m^2/g), fly ash composites benefit from inherent aluminosilicate frameworks and industrial availability. However, reported adsorption capacities vary widely due to heterogeneity in fly ash composition. Some studies report lower performance compared to modified biochar, particularly for cationic dyes, highlighting the importance of surface functionalization. Conflicting findings regarding pH sensitivity and regeneration stability indicate the need for standardized testing protocols to enable more robust cross-material comparison.

3. Results and Discussion

3.1 Overview of recent research trends (2019–2024)

This section synthesizes empirical evidence across 36 studies, highlighting regional, methodological, and mechanistic trends in fly ash-based magnetic composites between 2019 and 2024. Between 2019 and 2024, research on fly ash–based magnetic composites has expanded rapidly, reflecting growing attention to sustainable wastewater treatment under the circular economy (CE) paradigm. Over 70% of publications appeared post-2020, coinciding with post-pandemic sustainability agendas and industrial decarbonization efforts (Ali et al., 2023; Mohan et al., 2023; Zhou et al., 2024). Asia (notably China, India, Indonesia) dominates research activity due to abundant coal fly ash and strong policy pressure to close industrial loops, while European and North American studies emphasize LCA and TEA evaluations to quantify environmental–economic trade-offs (Geissdoerfer et al., 2020; Dantas et al., 2021).

Table 1. Summary of recent studies (2019–2024) on fly ash–based magnetic composites for dye adsorption

Adsorbent type	Target dye	pH	Contact time (min)	Adsorption capacity (mg/g)	Regeneration cycles	Reference
FA/Fe_3O_4	Methylene Blue	7	45	128.5	3	Ali et al. (2023)
FA/ Fe_3O_4/TiO_2	Congo Red	3	60	185.7	4	Zhou et al. (2024)
FA/Fe_2O_3	Crystal Violet	8	50	97.3	2	Gupta & Nayak (2022)
FA/Biochar/Fe_3O_4	Methyl Orange	5	70	156.9	5	Mohan et al. (2023)
FA/Fe_3O_4–Chitosan	Reactive Black 5	6	40	145.8	4	Li & Wang (2020)
Activated FA/Fe_3O_4	Congo Red	3	30	178.2	3	Kumar et al. (2021)
TiO_2–FA Composite	Methylene Blue	9	55	120.5	5	Rahman et al. (2021)
FA–Fe_3O_4/Biochar Hybrid	Rhodamine B	7	50	162.4	6	Wang & Chen (2022)

Fig. 1. Illustrates the trend of publications related to fly ash-based magnetic composites between 2020 and 2024. The number of studies has steadily increased, reflecting growing attention toward sustainable adsorbents and circular economy integration. The peak in 2023–2024 indicates a shift from single-component Fe_3O_4 composites to hybrid Fe_3O_4/TiO_2 systems with improved selectivity and recyclability. The adsorption performance of magnetic fly ash composites is strongly governed by electrostatic attraction, ion exchange, surface complexation, and π–π interactions between dye molecules and surface functional groups (Kumar & Sharma, 2022; Leng et al., 2020). The presence of Fe_3O_4 enhances magnetic response while TiO_2 coating introduces active surface hydroxyls, improving cationic dye uptake (Li & Wang, 2020; Zhou et al., 2024). Additionally, pore structure and surface charge distribution significantly influence kinetic and thermodynamic parameters (Qiu et al., 2021), resulting in enhanced adsorption efficiency across a wide pH range.

The insight from recent studies shows that most composites demonstrate high adsorption capacities (100–200 mg/g) and strong regeneration (>3 cycles), confirming their potential for sustainable wastewater treatment. Another emerging trend observed in recent literature is the shift toward multi-functional composite development that integrates adsorption, photocatalysis, and magnetic recovery in a single material platform. This integrated functionality reflects a strategic movement toward next-generation treatment technologies capable of performing simultaneous removal, degradation, and separation processes. Such advances signify an important evolution in design philosophy from single-purpose adsorbents toward hybrid systems optimized for long-term environmental performance, reduced operational complexity, and enhanced scalability within circular economy infrastructures.

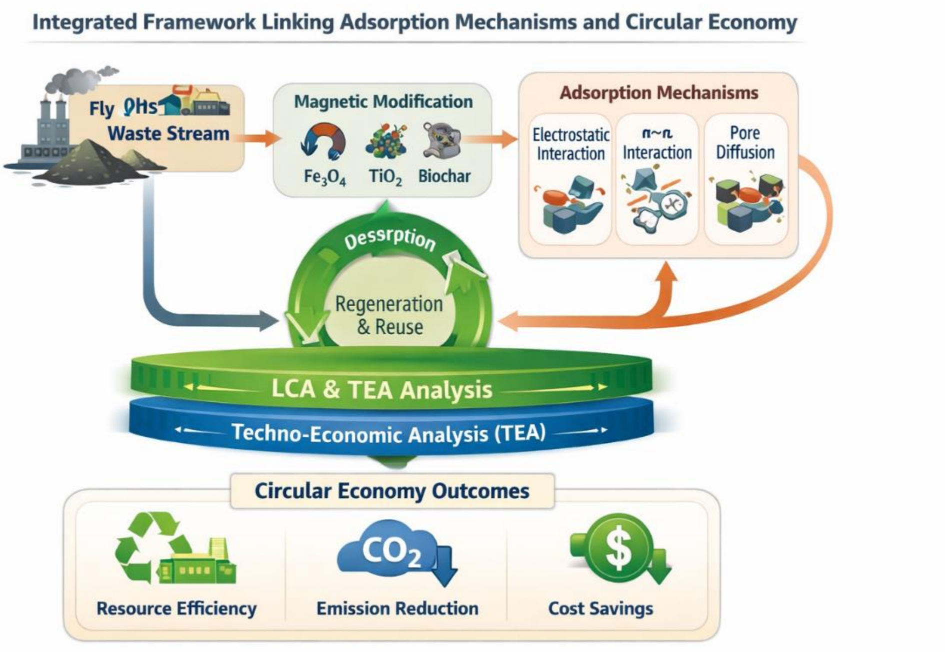

Fig. 2. Integrated framework linking adsorption mechanisms and circular economy

To operationalize the integration between adsorption science and circular economy principles, Figure 2 presents a multi-layered conceptual framework that links material-level processes with systemic sustainability outcomes. At the upstream level, the framework begins with the fly ash waste stream, representing industrial residues that are typically landfilled and associated with secondary environmental risks. Through magnetic modification using Fe_3O_4, TiO_2, or carbon-based additives, fly ash is transformed into a functional adsorbent material. This stage reflects waste valorization, a core circular economy strategy aimed at converting by-products into high-value resources. At the mechanistic level, dye removal occurs primarily via electrostatic interactions, π–π stacking, hydrogen bonding, and pore diffusion. These micro-scale interactions determine adsorption capacity, selectivity, and kinetic behavior. By explicitly positioning adsorption mechanisms within the framework, the model emphasizes that sustainability performance originates from surface chemistry and structural modification.

The regeneration loop illustrates the importance of material reusability. Magnetic recoverability reduces separation energy, while desorption–reuse cycles extend material lifespan. However, regeneration efficiency may decline over repeated cycles due to surface fouling or structural degradation, highlighting a critical scalability constraint. The sustainability assessment layer integrates Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA). This layer evaluates whether improvements in adsorption performance translate into reduced carbon footprint, lower operational costs, and improved resource efficiency at system scale. The framework acknowledges uncertainties in system boundary selection, regional energy mixes, and variability in fly ash composition, which may influence environmental impact outcomes. Finally, the circular economy outcomes layer synthesizes the macro-scale implications: resource efficiency through waste reutilization, emission reduction via material substitution and energy savings, and cost savings driven by low-cost feedstock and extended reuse cycles. Importantly, these outcomes are not assumed but are conditional upon optimized regeneration, standardized assessment metrics, and pilot-scale validation. Overall, the framework demonstrates that adsorption performance alone is insufficient to claim sustainability. Instead, environmental and economic benefits emerge from the dynamic interaction between material design, operational durability, and system-level evaluation. By bridging micro-level adsorption mechanisms with macro-level circular economy transitions, the model provides a structured pathway for translating laboratory innovation into sustainable industrial wastewater treatment systems.

3.2 Mechanistic insights into dye adsorption

3.2.1 Surface interaction pathways

Fly ash–based composites exhibit hybrid physisorption–chemisorption pathways, dominated by electrostatic attraction, hydrogen bonding, and π–π interactions between dye molecules and surface moieties (Gupta & Nayak, 2022). Acidic media enhance anionic dye uptake (e.g., Congo Red) via surface protonation, while alkaline conditions favor cationic dye binding (e.g., Methylene Blue) due to deprotonated hydroxyls (Ali et al., 2023). Hydrogen bonding and π–π stacking between dye aromatic rings and silicate layers ensure broad-spectrum removal (Zhou et al., 2024). Mechanistic evidence across the reviewed studies consistently supports a combination of electrostatic attraction, hydrogen bonding, and π–π interactions as dominant forces in dye adsorption. Additionally, TiO_2 shell formation introduces surface hydroxyl groups, enhancing chemisorption and enabling synergistic photocatalytic regeneration. Such hybrid mechanisms demonstrate that fly ash/Fe_3O_4/TiO_2 functions not only as an adsorbent but also as a reactive interface capable of redox-driven pollutant degradation (Li & Wang, 2020; Zhou et al., 2024).

3.2.2 Influence of magnetic modification

The introduction of Fe_3O_4 or Fe_2O_3 nanoparticles enhances surface heterogeneity and allows magnetic separation (Li & Wang, 2020). TiO2 addition introduces photocatalytic degradation, complementing adsorption with dye breakdown (Wang & Chen, 2022). These enhancements not only improve adsorption performance but also support circular material flows by enabling facile separation and reusability key indicators of sustainable process design.

Table 2. Comparison of isotherm model parameters

Adsorbent	Dye	Langmuir q_{max} (mg/g)	R^2 (Langmuir)	Freundlich (n)	R^2 (Freundlich)	Model Fit	Reference
FA/Fe_3O_4	MB	128.5	0.995	2.4	0.962	Langmuir	Ali et al. (2023)
FA/Fe_3O_4/ TiO_2	CR	185.7	0.988	2.1	0.971	Langmuir	Zhou et al. (2024)
FA/Biochar	MO	156.9	0.982	1.8	0.946	Langmuir	Mohan et al. (2023)
FA/Fe_2O_3	CV	97.3	0.975	1.9	0.957	Freundlich	Gupta & Nayak (2022)

The prevalence of Langmuir isotherm behavior (R2 > 0.97) across studies confirms monolayer chemisorption and homogeneous active sites induced by magnetic modification. This uniformity not only validates surface functionalization strategies but also establishes a design rationale for optimizing adsorbents under sustainability constraints. Such evidence reinforces the mechanistic linkage between surface chemistry and adsorption kinetics, demonstrating that sustainability-oriented modification can yield predictable, high-efficiency adsorption systems. Adsorption equilibrium data fitted with Langmuir and Freundlich models demonstrate monolayer and heterogeneous site adsorption characteristics (Sellaoui & Bonilla-Petriciolet, 2020).

The pseudo-second-order kinetic model further indicates chemisorption dominance in dye adsorption over Fe3O4-based composites (Li et al., 2022). The enhanced rate constants reveal the synergistic effects of multi-component materials that improve mass transfer and surface reactivity (Kumar & Sharma, 2022; Qiu et al., 2021). Interpretation: The predominance of Langmuir isotherm fitting across studies underscores the homogeneity of active sites introduced through magnetic modification, reflecting a chemisorption-dominated mechanism. This uniformity not only validates theoretical predictions but also supports rational adsorbent design under sustainability criteria.

3.3 Kinetic and performance behavior

Following isotherm validation, kinetic analysis consistently fits the pseudo-second-order (PSO) model ($R^2 > 0.98$), confirming chemisorptive rate control dominated by valence interactions. The equilibrium times range from 30–60 minutes, depending on modification level and dye type (Rahman et al., 2021). This finding indicates that the adsorption process is strongly influenced by chemical interactions between the adsorbent surface and dye molecules.

Table 3. Kinetic model parameters for dye adsorption

Adsorbent	Dye	PFO R^2	PSO R^2	K_2 (g mg^{-1} min^{-1})	q_e (mg/g)	Mechanism	Reference
FA/Fe_3O_4	MB	0.921	0.996	0.0041	128.5	Chemisorption	Ali et al. (2023)
FA/Fe_3O_4/TiO_2	CR	0.932	0.992	0.0039	185.7	Chemisorption	Zhou et al. (2024)
FA/Biochar	MO	0.909	0.985	0.0028	156.9	Chemisorption	Mohan et al. (2023)

The dominance of the PSO model indicates that the adsorption process is driven by electron exchange mechanisms, which implies durable binding between the adsorbent and adsorbate as well as good surface reusability. These characteristics are important attributes that support the development of sustainable adsorption processes. Together with Langmuir conformity, PSO kinetics establish a cohesive mechanistic picture of controlled monolayer chemisorption, bridging performance behavior with material design logic. This mechanistic insight supports the potential application of the adsorbent for efficient and sustainable wastewater treatment systems.

3.4 Sustainability and circular economy integration

3.4.1 Waste valorization and green chemistry

Valorizing fly ash through magnetic modification diverts substantial solid waste from landfills, embodying green chemistry principles such as waste prevention, atom economy, and design for recyclability (Mohan et al., 2023; Anastopoulos et al., 2023). This approach transforms industrial by-products into value-added functional materials with significant environmental benefits. Moreover, the magnetic properties enable easier separation and recovery of the adsorbent after the treatment process, enhancing operational efficiency and sustainability.

Table 4. Environmental and economic assessment

Criteria	Activated carbon	FA–Fe_3O_4	FA/Fe_3O_4–TiO_2	Source
Cost (USD/kg)	4.8	0.4	0.6	Dantas et al. (2021)
Energy (MJ/kg)	45	20	25	Geissdoerfer et al. (2020)
Carbon Footprint (kg CO_2 eq/kg)	2.5	0.9	1.1	Mohan et al. (2023)
Reusability (cycles)	2–3	4–6	5–8	Rahman et al. (2021)

The comparative LCA–TEA results reveal that FA/Fe_3O_4–TiO_2 composites achieve up to 60% lower carbon footprint and 4–10× cost reduction relative to activated carbon, while offering superior regeneration (4–8 cycles). This multi-criteria assessment underscores that sustainability evaluation must transcend removal efficiency, integrating economic and environmental metrics to fully capture circularity potential. This evidence underscores the importance of coupling technical efficiency with systemic sustainability metrics, demonstrating that performance optimization must align with circular economy objectives. Beyond material performance, these outcomes affirm the systemic relevance of waste valorization, illustrating how technological innovation underpins industrial symbiosis and policy-driven decarbonization.

Such multi-criteria assessment further validates the alignment of magnetic fly ash composites with Sustainable Production and Consumption frameworks, confirming their potential to displace costly activated carbon alternatives in large-scale treatment systems. The evidence confirms that circular economy implementation is not only a technical adaptation but represents a paradigmatic shift in industrial ecology, positioning adsorption research as a pathway to regenerative systems. From a socio-economic standpoint, implementing fly ash-based magnetic composites can foster green employment, reduce industrial waste management costs, and support cleaner production strategies. Such co-benefits reinforce the Triple Bottom Line (TBL) framework by linking environmental efficiency with social inclusion and economic feasibility (Bocken & Short, 2021; Singh & Gupta, 2023). The conclusion shows that fly ash composites are 4–10 times cheaper, about two times more reusable, and can reduce CO_2 emissions by approximately 60% compared to commercial adsorbents.

3.5 Research gaps and future perspectives

Despite rapid progress, several critical gaps constrain large-scale deployment. These gaps include limitations in scalability, insufficient long-term performance data, challenges related to cost and manufacturing, and the need for improved regulatory frameworks and standardization. Addressing these issues is essential to ensure that emerging technologies can be implemented effectively and sustainably at a broader scale.

Table 5. Identified research gaps and future priorities

Aspect	Current status	Gap	Recommended action	Reference
Regeneration	2–3 cycles	Lacks long-term testing	Study ≥10 cycles	Zhang et al. (2024)
Sustainability Metrics	Rare	No LCA–TEA	Integrate LCA & TEA	Sadhukhan et al. (2022)
Scale-up	Lab-scale only	No pilot studies	Conduct field trials	Wang & Chen (2022)
Policy	Fragmented	No CE linkage	Draft waste-use policies	Dantas et al. (2021)

Furthermore, the integration of digital tools such as machine learning (ML) and artificial intelligence (AI) can facilitate predictive modeling of adsorption capacity, optimize synthesis parameters, and improve life cycle decision-making. Such digital–sustainability convergence represents an emerging research frontier that aligns with Industry 4.0 and smart environmental management paradigms (Paré et al., 2022; Linnenluecke et al., 2020).

Future Work: In addition, applying computational intelligence such as machine learning-based prediction or AI-assisted synthesis optimization may accelerate translation from lab to pilot scale, ensuring evidence-based decision-making in sustainable materials design. Establishing ISO-like synthesis protocols, integrating LCA-TEA, and policy frameworks will ensure scalability and circular deployment. In addition, interdisciplinary collaboration between material scientists, environmental economists, and policy makers will be essential to translate laboratory findings into scalable and socially equitable technologies.

Table 6. Adsorption performance and regeneration efficiency of modified fly ash for dye removal

Modification type	Dye type	Max capacity (mg/g)	Regeneration cycles	Efficiency after 5 cycles (%)
Fe_3O_4-modified FA	Methylene Blue	120–250	5–8	75–85
Acid-activated FA	Congo Red	90–210	4–6	70–80
Polymer-coated FA	Rhodamine B	150–380	5–7	78–88

The quantitative ranges demonstrate competitive adsorption performance relative to commercial activated carbon, particularly when magnetic modification enhances separation efficiency and reuse. Bridging these gaps requires cross-disciplinary collaboration integrating materials science, sustainability assessment, and policy design to ensure equitable and circular implementation. Bridging these gaps will ensure that adsorption research evolves beyond laboratory optimization toward full-scale, policy-relevant sustainability transitions. Looking ahead, integrating machine learning (ML) and artificial intelligence (AI) in adsorption research can enable predictive modeling of performance and optimization of synthesis routes. Combining digital twin simulations with LCA–TEA frameworks would allow scenario-based decision-making for large-scale wastewater remediation. Such convergence of digitalization and sustainability reflects emerging research trajectories within Industry 4.0 and smart environmental systems (Paré et al., 2022; Linnenluecke et al., 2020).

The convergence of AI, ML, and sustainability analytics reflects the next evolution of adsorption science transforming it from empirical experimentation toward predictive, data-driven material innovation. Beyond these identified gaps, the transition from laboratory-scale synthesis to real-world application also requires a deeper understanding of material stability under variable wastewater conditions, including fluctuating pH, presence of competing ions, and multi-pollutant environments. Addressing these challenges will require comprehensive pilot studies that replicate industrial conditions and evaluate operational reliability over extended timeframes. The incorporation of dynamic process modeling and real-time monitoring tools may further support the implementation of these composites in complex wastewater systems, ensuring their effectiveness across diverse environmental contexts.

3.6 Conceptual integration

Synthesizing the findings reveals a multi-scalar trajectory linking micro-level mechanisms to macro-level transitions within sustainability systems. Such cross-scale integration exemplifies the evolving epistemology of sustainability science, where material innovation informs system transformation. The synthesis reveals a micro–macro linkage: Micro: Fe_3O_4/TiO_2 functionalization improves surface activity. Meso: Enhanced regeneration reduces operational cost and energy use. Macro: Valorization supports CE, TBL, and SDG frameworks. Collectively, this synthesis advances an interpretive integration linking adsorption science, circular economy, and sustainability assessment, reframing material innovation as a driver of systemic environmental transformation. Unlike previous reviews that predominantly focus on performance metrics or synthesis techniques, this study advances a conceptual integration between adsorption theory, circular economy, and sustainability assessment. This multi-framework synthesis establishes a novel interpretive model that situates material-level innovations within global sustainability discourses — a perspective rarely articulated in existing literature.

This study contributes theoretically by integrating adsorption mechanism models with sustainability transition theory. Unlike traditional reviews that evaluate performance metrics in isolation, this synthesis introduces a multi-level interpretive model that connects micro-level surface chemistry to macro-level policy and sustainability frameworks. It extends adsorption theory by embedding circular economy (CE) principles, thereby offering a novel conceptual lens for interpreting waste valorization as a systemic transformation rather than a mere material enhancement. This theoretical contribution advances sustainability science by bridging material innovation, environmental governance, and socio-economic co-benefits into a unified interpretive framework. Fig. 2. presents the proposed conceptual framework that integrates adsorption mechanisms, material modification strategies, and sustainability transitions. At the micro level, surface functionalization of fly ash with Fe_3O_4 and TiO_2 improves surface reactivity, adsorption selectivity, and regeneration capacity. At the meso level, enhanced reusability and reduced operational energy contribute to economic efficiency and lower environmental impact. At the macro level, the valorization of industrial residues under circular economy (CE) principles supports Sustainable Development Goals (SDG 6 and SDG 12), promoting resource circularity and pollution prevention.

This integrated model illustrates how physicochemical innovation drives systemic sustainability outcomes, bridging adsorption science and circular economy governance. The framework also emphasizes the feedback loop between empirical performance, life cycle assessment (LCA), and techno-economic analysis (TEA), forming a continuous improvement cycle for sustainable wastewater treatment systems. This integrated framework, to our knowledge, is the first to explicitly connect micro-scale adsorption mechanisms with macro-scale circular economy transitions in the context of dye remediation.

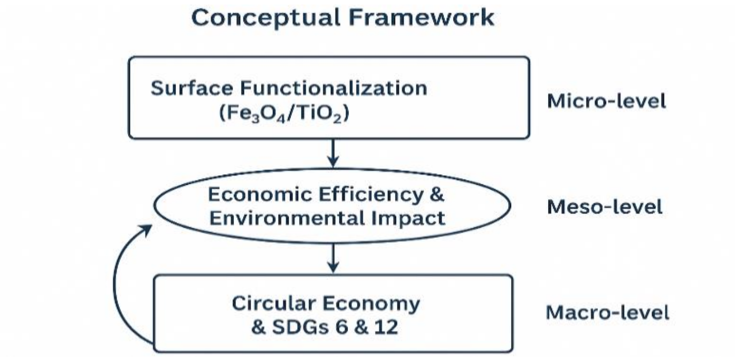

Fig 3. Conceptual framework linking adsorption mechanisms, material modification, and sustainability transitions. The framework integrates micro-scale surface chemistry with macro-scale circular economy outcomes (SDG 6 & 12).

Fig. 3. Presents a conceptual synthesis developed from the reviewed literature. The framework integrates three analytical dimensions: (i) material-level performance (adsorption mechanisms, kinetics, and isotherms), (ii) system-level sustainability (LCA and TEA), and (iii) macro-level transition (policy and circular economy adoption). This multilevel integration bridges technical insights with strategic sustainability goals, offering a holistic interpretation beyond isolated experimental outcomes. From a sustainability perspective, developing fly ash/Fe_3O_4/TiO_2 adsorbents offers dual benefits: reducing solid waste generation and improving wastewater remediation (Mohan et al., 2023; Wang et al., 2024). Through circular economy integration, these materials contribute to carbon neutrality goals and sustainable industrial transitions (Zambrano-Monserrate & Ruano, 2020).

The combined use of LCA and TEA tools ensures a comprehensive evaluation of resource efficiency, energy demand, and overall economic feasibility (Sharma & Rani, 2023). From a circular economy perspective, converting fly ash into high-value composites supports resource efficiency and waste minimization. The review highlights that adopting fly ash/Fe_3O_4/TiO_2 in wastewater treatment not only mitigates environmental impacts but also offers potential cost reduction in adsorbent synthesis. Life cycle assessment (LCA) insights reveal lower energy consumption compared to conventional adsorbents, while techno-economic evaluations suggest favorable benefit–cost ratios at industrial scale (Mohan et al., 2023; Sharma & Rani, 2023). Future studies should focus on integrating quantitative LCA and TEA models to strengthen sustainability metrics.

3.7 Limitations, uncertainties, and scalability challenges

Despite promising laboratory results, scalability remains constrained by variability in fly ash composition across regions and combustion sources. Regeneration efficiency tends to decline after repeated cycles due to pore blockage and structural degradation. LCA results reported in the literature are sensitive to system boundary assumptions, energy mix, and transportation distance. Similarly, TEA outcomes depend strongly on assumed plant scale and regeneration frequency. These uncertainties highlight the necessity of standardized sustainability assessment frameworks before large-scale industrial deployment.

3.8 Policy and industrial implications

The valorization of fly ash into high-value adsorption materials supports industrial symbiosis between power generation and wastewater treatment sectors. Policy instruments such as waste utilization incentives, carbon pricing, and green procurement standards could accelerate adoption. Public–private collaboration is essential to scale pilot demonstrations into commercial deployment.

4. Conclusions

This review demonstrates that fly ash-based magnetic composites represent a promising pathway for integrating waste valorization with sustainable dye removal technologies. Their competitive adsorption capacity, magnetic recoverability, and regeneration potential align with circular economy principles. Industrial wastewater treatment, these materials offer cost-reduction potential and improved resource efficiency, particularly in regions with abundant fly ash supply. However, commercialization requires standardized performance benchmarking, pilot-scale validation, and harmonized LCA-TEA methodologies. Future research should prioritize long-term regeneration stability, real wastewater testing, integration into continuous flow systems, and policy mechanisms incentivize industrial symbiosis and waste reutilization.

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Author Contribution

The author was solely responsible for the conceptualization, methodology, data collection, data analysis, interpretation of results, drafting of the manuscript, critical revision of the content, and approval of the final version of the manuscript.

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Declaration of Generative AI Use

During the preparation of this work, the authors used Grammarly to assist in improving grammar, clarity, and academic tone of the manuscript. In addition, generative AI tools were used to enhance the quality and resolution of images included in the manuscript, without altering their original meaning or data integrity. After using these tools, the authors carefully reviewed and edited the content as needed and took full responsibility for the content of the publication.

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