SJIF Impact Factor (2025): 8.688| ISI I.F. Value: 1.241| Journal DOI: 10.36713/epra2016 ISSN: 2455-7838(Online)
EPRA International Journal of Research and Development (IJRD)
Volume: 10 | Issue: 11 | November 2025 - Peer Reviewed Journal

SILICA-BASED HYBRID MATERIALS FOR THE SIMULTANEOUS ADSORPTION OF MULTIPLE DYE POLLUTANTS: A REVIEW OF SYNERGISTIC EFFECTS AND ADSORPTION MECHANISMS

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Article DOI: https://doi.org/10.36713/epra25012
DOI No: 10.36713/epra25012

ABSTRACT

The increasing complexity of industrial wastewater, particularly from textile and pharmaceutical industries in the United States, necessitates advanced treatment technologies capable of simultaneously removing multiple dye pollutants. Silica-based hybrid materials have emerged as promising adsorbents due to their high surface area, tunable porosity, chemical stability, and ease of functionalization. This review synthesizes recent advances in synthesis strategies, adsorption mechanisms, and synergistic effects in multi-component dye systems. Particular emphasis is placed on competitive and cooperative interactions, determinants of selectivity, and modeling frameworks that regulate adsorption in complex mixtures. Structure–performance relationships are critically assessed in terms of crystallinity, porosity, and surface chemistry, while optimization strategies underscore the importance of response surface methodology, process intensification, and machine learning in scaling up treatment. Regeneration and reusability studies highlight the economic feasibility of silica-based hybrids, supported by techno-economic and life cycle assessments that demonstrate the environmental benefits of bio-based precursors and integration into circular economy practices. Emerging directions, including pH- and temperature-responsive hybrids, adsorption–photocatalysis integration, and digital twin optimization, further underscore the potential of these materials for next-generation water treatment. This review consolidates both fundamental insights and practical implications of silica-based hybrid adsorbents, advancing their translation from laboratory research to real-world industrial wastewater management.

KEYWORDS: *Silica-Based Hybrids, Multi-Component Adsorption, Synergistic Effects, Dye Pollutants, Adsorption Mechanisms*

1. INTRODUCTION

Water pollution continues to be a major environmental issue in the United States (US), with industrial wastewater discharge posing significant threats to national water resources [1]. There have been significant reductions in toxic chemical releases over the years. Despite overall reductions, concerns persist about hazardous chemicals bypassing sewage treatment plants and polluting waterways [2]. The textile industry, particularly, produces over 2 million gallons of wastewater per day, and is responsible for the 17-20% of industrial water pollution globally attributed to dyeing and finishing [3]. Despite regulations, such as the Clean Water Act and the National Pollutant Discharge Elimination System (NPDES), compliance remains difficult, as industrial processes become more complex, and the economic burden of polluted waterways is estimated to exceed $1 trillion in infrastructure spending across the country [4].

Synthetic dyes are of particular concern as they are chemically stable, non-biodegradable, and are visible at concentrations lower than 1 ppm [5]. Conventional effluents from textile, pharmaceutical, food, and paper industries remain in the environment for several decades. For instance, azo compounds, the most widely used dye, exhibit degradation times of up to 50 years [6]. Numerous studies in the U.S. have reported their cancerous, mutagenic, and allergenic effects, as well as ecological impacts such as diminished photosynthesis, bioaccumulation in aquatic species, and ecosystem disruption [6-8]. In industrial discharges, multiple dyes coexist, creating complex wastewater streams that challenge conventional treatments like coagulation–flocculation, oxidation, and biological degradation [5]. Adsorption has been identified as an alternative, due to its ease of operation, cost-effectiveness, minimal secondary pollution, and compatibility with existing water treatment infrastructure [5]. While activated carbon remains widely applied, research has increasingly shifted toward advanced adsorbents, including nanomaterials and hybrid systems, that offer higher efficiency and selectivity [9].

Among recent scientific advancements, there has been a significant interest in silica-based hybrid materials in the U.S. because of the abundance, low cost, and regulatory acceptance of silica [10]. Mesoporous silica, with surface areas exceeding 1000 m^2/g and tunable pore structures, provides an ideal platform for developing advanced adsorbents. Hybridization techniques, including polymer grafting, metal oxide loading, and organic ligand modification, can improve the adsorption capacity, selectivity, and recyclability, which render these materials as potential multi-pollutant sorbents [11].

Despite these advancements, most research has concentrated on the single-dye systems, overlooking the competitive interactions that define real wastewater. Key gaps remain regarding how molecular size, charge, and π–π interactions affect concurrent dye adsorption and how functionalization approaches modulate these mechanisms [12]. These deficiencies diminish the prediction and practical optimization for U.S. industrial applications. This review synthesizes the existing knowledge on silica-based hybrid systems for the simultaneous adsorption of various dyes, focusing on synergistic effects and adsorption mechanisms to support the development of future-generation technologies for treating dye wastewater.

2. SYNTHESIS STRATEGIES AND STRUCTURAL DESIGN OF SILICA-BASED HYBRID ADSORBENTS

The synthesis of silica-based hybrid adsorbents has progressed substantially, driven by their high surface area, tunable pore size, and structural stability, which make them highly effective for dye removal [13]. Considerable research has been directed toward incorporating either organic or inorganic components into silica matrices to generate hybrid systems that leverage the synergistic advantages of silica's chemical versatility and stability with the tailored functionality of modifiers [13, 14]. A variety of synthetic approaches, including sol-gel synthesis, hydrothermal treatment, co-condensation, impregnation, and emerging template-free methods, have been employed to fabricate hybrids with optimized surface characteristics and enhanced adsorption performance.

2.1 Sol-Gel and Template-Directed Methods

The sol-gel process remains the most versatile and widely employed method for preparing silica-based hybrids. It is based on the hydrolysis and condensation of molecular precursors, most commonly tetraethyl orthosilicate, under controlled pH and temperature conditions. This route enables the production of materials in various forms, including powders, gels, films, and nanoparticles [15]. When combined with structure-directing agents such as surfactants or block copolymers, sol-gel chemistry facilitates the synthesis of mesoporous silica frameworks such as MCM-41, SBA-15, and KIT-6 [15]. These ordered structures exhibit uniform pore size distributions (2–50 nm), high densities of silanol groups, and large surface areas, which provide excellent platforms for subsequent functionalization with dye-attracting groups [16]. Template removal is typically achieved through calcination or solvent extraction, yielding highly porous architectures suitable for multicomponent dye adsorption [17].

2.2 Hydrothermal and Co-Condensation Approaches

Hydrothermal synthesis enables the crystallization of silica hybrids under relatively mild conditions (100–150 °C), yielding materials with uniform grain size, high purity, and reduced agglomeration [18]. This method has facilitated the preparation of silica-supported inorganic phases, such as titanate–silica and alumina–silica hybrids, which exhibit enhanced stability and adsorption performance. By contrast, co-condensation directly incorporates functional organosilanes with silica precursors during synthesis [19]. This one-step strategy introduces higher densities of functional groups than post-grafting, thereby increasing the affinity of the hybrid material toward dye molecules [19]. For example, amine-functionalized silica obtained through co-condensation demonstrates improved adsorption efficiency as a result of electrostatic interactions with anionic dyes [20].

2.3 Impregnation and Polymer-Silica Hybrids

Impregnation methods are employed to incorporate organic ligands or polymers into pre-formed silica frameworks, typically under vacuum or thermal conditions. This approach has been applied to immobilize ligands such as CMPO and TODGA within silica matrices, thereby enhancing selectivity for charged molecules [21]. In situ polymerization has also been utilized to synthesize silica–polymer composites, including SiO_2–poly (vinyl alcohol) and SiO_2–styrene-divinylbenzene hybrids [21]. These materials combine the mechanical stability of silica with the hydrophilic and adsorptive properties of polymers, enabling the simultaneous uptake of both cationic and anionic dyes [15]. Furthermore, structural optimization, such as the design of macroporous silica (pore size 50–600 nm) or mesoporous SBA-15 derivatives with surface areas exceeding 500 m^2/g, significantly accelerates adsorption kinetics and enhances dye capacity [21].

2.4 Template-Free and Green Synthesis Approaches

More recently, template-free approaches have been investigated to simplify synthesis, lower costs, and enhance scalability [22]. Template-free sol–gel methods and precipitation routes, commonly starting from sodium silicate, produce porous silica particles without the need for surfactants or organic templates [23]. Agricultural wastes, including sugarcane bagasse ash and rice husks, have also been utilized as sustainable and economical silica sources for the preparation of mesoporous hybrids [15]. In some cases, the residual carbonaceous matter present in these biomass-derived silicas provides additional adsorption sites, generating multifunctional hybrids with both hydrophilic and hydrophobic characteristics that are particularly effective for the simultaneous adsorption of diverse dye pollutants [24].

3.0 MULTI-COMPONENT ADSORPTION BEHAVIOR AND COMPETITIVE INTERACTIONS

Adsorption in multi-component dye systems is more complex than in single-component systems due to the simultaneous competition of different molecules for limited active sites [25]. In silica-based hybrid materials, these interactions often result in reduced adsorption of individual dyes compared to single-dye systems, with decreases in adsorption capacity [26]. Such antagonistic effects arise from competition for surface sites, steric hindrance caused by molecular size differences, and overlapping adsorption mechanisms, including π–π stacking and hydrogen bonding. Nevertheless, cooperative or synergistic effects may also occur when the presence of one dye enhances the uptake of another through secondary interactions or improved accessibility of adsorption sites [25].

3.1 Modeling Multi-Component Adsorption

To account for these complex interactions, several mathematical models have been applied. The Extended Langmuir (EL) model is widely used for describing binary and ternary dye adsorption but often becomes inadequate when adsorbates differ substantially in size or affinity [27]. Modified formulations, such as the Competitive Langmuir–Freundlich model, better capture surface heterogeneity and energy distribution [28]. The Ideal Adsorbed Solution Theory (IAST) provides more reliable predictions of multicomponent equilibria, although its application is limited by the computational demands of implicit calculations [29]. More recent approaches, including explicit multi-component isotherm models and the JAMM (Jain–Srivastava–Malik–Mondal) equation, demonstrate improved predictive capacity for binary dye mixtures with markedly different saturation capacities [30].

3.2 Selectivity and Competitive Mechanisms

Selectivity in dye mixtures is primarily governed by electrostatic and molecular interactions, with the point of zero charge (PZC) of the silica-based hybrid adsorbent serving as a key determinant. For example, cationic dyes such as Methylene Blue are typically favored under acidic to neutral pH conditions, whereas anionic dyes like Congo Red are preferentially adsorbed in alkaline environments. The balance between surface hydrophilicity and hydrophobicity further modulates selectivity, enabling certain hybrids to preferentially adsorb one dye species even under competitive conditions. Antagonistic effects are often observed in binary mixtures, where strong ion-pair formation or steric exclusion limits simultaneous adsorption. Conversely, synergistic effects may arise when the presence of one dye enhances surface wettability or facilitates multilayer stacking, thereby promoting the uptake of another dye.

3.3 Performance in Silica-Based Hybrid Systems

Silica-polymer hybrids exhibit strong adsorption potential in multi-component systems, with materials such as SBA-15/PAMAM achieving capacities up to 1428 mg/g for anionic dyes, influenced by pH and ionic strength [15]. Adsorption kinetics are generally described by the pseudo-second-order model, while equilibrium data align with the Freundlich isotherm, reflecting heterogeneous surface characteristics and energy distribution [31]. Competitive adsorption is evaluated using selectivity factors and competitive coefficients, which compare experimental uptake with theoretical values to determine whether interactions are competitive, cooperative, or neutral [31]. Spectroscopic analyses, particularly FTIR and UV–vis, provide evidence of altered binding modes in multi-component systems compared with single-dye adsorption, with observed shifts in peak positions and intensities indicating modified molecular environments under competitive conditions [32, 33].

4.0 SYNERGISTIC EFFECTS: MECHANISMS, QUANTIFICATION, AND OPTIMIZATION

Synergistic effects in multi-dye adsorption occur when the presence of one dye enhances the uptake of another, resulting in overall adsorption capacities exceeding the sum of individual contributions [34]. These interactions are particularly relevant in systems containing dyes of opposite charges or complementary functional groups, as co-adsorption can create additional binding opportunities [34]. In silica-based hybrid materials, such effects are increasingly investigated because they can markedly improve the treatment efficiency of complex dye mixtures frequently encountered in textile and industrial effluents [35].

4.1 Mechanisms of Synergistic Adsorption

Synergistic adsorption mechanisms are multifaceted and context-dependent, typically involving cooperative binding, dye–dye complexation, and the formation of additional adsorption sites through dye–adsorbent–dye interactions [36]. The primary forces driving these processes include electrostatic attraction, hydrogen bonding, π–π stacking, and cation-exchange. For instance, chitosan–silica hybrids modified with tannic acid and nanocellulose have demonstrated 40–210% higher uptake of cationic dyes in mixed systems due to enhanced electrostatic and π–π interactions [36]. Similarly, silica obtained from agricultural waste such as bagasse ash has exhibited preferential adsorption of anionic dyes in the presence of cationic counterparts, although antagonistic effects may also occur under certain conditions [37]. Moreover, silica–triazole hybrids and MOF–silica composites illustrate how structural and chemical modifications enhance selectivity and stability, providing adaptable frameworks for both dye and heavy metal adsorption [38].

4.2 Quantification of Synergistic Effects

Accurate estimation of synergistic effects is essential for systematic evaluation. Several indices have been proposed for this purpose, including cooperative coefficients that compare observed adsorption capacities with theoretical expectations, relative adsorption ratios, and selectivity coefficients [39]. Enhancement factors further aid interpretation by quantifying the fold increase in uptake relative to single-component dye adsorption [30]. While exceptionally high enhancement factors are frequently reported for gas-phase adsorption, aqueous dye systems typically exhibit more moderate [39]. These quantitative assessments are complemented by spectroscopic analyses such as FTIR and XPS, which help verify synergistic interactions through observable shifts in functional group behaviour and changes in binding energy profiles [40].

4.3 Optimization Strategies

Optimization of synergistic adsorption requires precise regulation of operational conditions. Statistical design frameworks such as response surface methodology and central composite design provide systematic approaches for evaluating the effects of key variables, including solution pH, initial dye concentration, adsorbent dosage, contact time, and temperature [41]. In many cases, optimum synergy is reported within the pH range of 4–8, where electrostatic interactions are most favorable [42]. Furthermore, competitive–cooperative models support prediction of the conditions under which synergism predominates over antagonism, a critical consideration for avoiding competitive inhibition that can diminish adsorption efficiency [43].

4.4 Integrated Hybrid Processes beyond Adsorption

The scope of synergy extends beyond adsorption alone to integrated systems such as adsorption–photocatalysis. Nearly complete dye removal (up to 99.6%) has been achieved using silica-supported TiO_2 and carbon–silica hybrids by coupling adsorption with photocatalytic decomposition [34]. In these systems, adsorption localizes pollutants at catalytic sites, while photocatalysis regenerates the adsorptive capacity through the breakdown of retained molecules, establishing a self-sustaining cycle of removal [44]. This dual mechanism demonstrates the strong potential of silica-based hybrids for multi-dye treatment and underscores their relevance when combined with advanced remediation technologies.

5.0 MATERIAL CHARACTERIZATION AND STRUCTURE-PERFORMANCE RELATIONSHIPS

5.1 Crystallinity and Framework Ordering

Characterization of silica-based hybrid adsorbents begins with assessing their structural order, as framework integrity is closely linked to adsorption performance. X-ray diffraction (XRD) is widely applied to evaluate mesostructural features [45]. For ordered mesoporous silicas such as SBA-15, small-angle XRD typically displays three distinct reflections [(100), (110), (200)] at $2\theta \approx 0.96°$, $1.45°$, and $1.70°$, confirming the presence of a two-dimensional hexagonal p6mm pore arrangement [46]. In the wide-angle region, a broad feature around $2\theta \approx 22°$ is observed, characteristic of amorphous silica [46]. The sharpness and intensity of diffraction peaks indicate long-range structural order, while peak broadening suggests partial disorder or reduced domain size. Complementary small-angle X-ray or neutron scattering (SAXS/SANS) provides further quantification of pore periodicity and size distributions, reinforcing that templated mesoporous silicas preserve highly uniform pore networks both before and after functionalization [47].

5.2 Surface Area and Porosity Analysis

Nitrogen physisorption remains the benchmark technique for determining surface area, pore volume, and pore size distribution in mesoporous silicas. High Brunauer-Emmett-Teller (BET) surface areas (300–900 m^2/g) and pore volumes (0.5–1.0 cm^3/g) are closely associated with enhanced dye adsorption capacities [48]. Functionalization with organic or polymer moieties generally decreases BET area and pore volume through partial pore filling, while simultaneously tailoring adsorption selectivity. Pore size distribution analysis by the Barrett–Joyner–Halenda (BJH) method shows that ordered silicas exhibit type IV isotherms with H1 hysteresis loops, confirming uniform cylindrical mesopores [49]. Pore sizes within the 5–15 nm range promote the diffusion of large dye molecules and reduce steric hindrance in multi-dye systems, rendering hierarchical porosity particularly advantageous for simultaneous adsorption [50].

5.3 Chemical and Surface Characterization

Fourier-transform infrared spectroscopy (FTIR) enables rapid identification of both the silica framework and surface functional groups [45]. Unmodified mesoporous silica exhibits intense Si–O–Si stretching at ~1100 cm^{-1} and broad O–H stretching near 3400 cm^{-1} arising from surface silanols. Following functionalization, additional vibrational bands corresponding to carboxyl, amine, or aromatic groups emerge, confirming covalent grafting [45]. X-ray photoelectron spectroscopy (XPS) complements FTIR by providing quantitative information on surface composition and chemical states [51]. In amine-functionalized hybrids, N 1s spectra are deconvoluted into distinct components associated with different bonding environments, while C 1s spectra distinguish adventitious carbon from grafted C–N or C–O bonds [52]. These spectroscopic signatures confirm functionalization and serve as reliable indicators of adsorption interactions with charged or aromatic dye molecules.

5.4 Morphological Characterization

Scanning electron microscopy is employed to examine particle size and shape, while transmission electron microscopy directly images internal pore ordering. Ordered mesoporous silicas display hexagonally arranged channels under TEM, with pore diameters consistent with BET-derived values [53]. Energy-dispersive X-ray spectroscopy mapping verifies the homogeneous distribution of grafted elements, whereas atomic force microscopy quantifies nanoscale roughness, which enhances adsorption by providing additional surface binding sites [53]. These microscopy techniques confirm that mesostructural integrity is preserved after hybridization and provide visual correlation with adsorption performance.

5.5 Thermal Stability and Composition

Thermogravimetric analysis (TGA) shows an initial weight loss below 100 °C due to water desorption, followed by distinct decomposition steps between 200–500 °C corresponding to organic moieties [54]. The total organic weight fraction is determined by comparing hybrid and pristine samples. Differential scanning calorimetry complements TGA by detecting glass transitions or phase changes of grafted polymers [55]. Together, these analyses establish safe regeneration conditions for spent adsorbents and confirm their durability under wastewater treatment scenarios.

5.6 Advanced Characterization Approaches

Solid-state nuclear magnetic resonance provides mechanistic insight into adsorption processes. ^{29}Si MAS NMR distinguishes Q^4 (fully condensed SiO_4) from Q^3 (silanol-containing) sites, enabling quantification of framework connectivity, while ^{13}C CPMAS NMR confirms the incorporation and stability of grafted organic groups [52]. In situ FTIR and Raman spectroscopy enable real-time monitoring of dye binding, evidenced by shifts in functional group vibrations upon adsorption [54]. Dynamic light scattering and ζ-potential measurements probe colloidal stability, which is critical for ensuring consistent adsorption under varying pH conditions [56].

5.7 Structure-Performance Correlations for Multi-Dye Systems

Large BET surface areas and accessible mesopores enhance dye adsorption capacity, while selective functionalization governs affinity toward cationic or anionic dyes. Amine-functionalized silicas preferentially adsorb sulfonated azo dyes through electrostatic interactions, whereas carboxylated surfaces favor cationic basic dyes [57]. Hierarchical porosity promotes co-adsorption of multiple dyes by reducing competitive effects and improving mass transfer [58]. Synergistic interactions can also occur, where the binding of one dye facilitates the uptake of another. By systematically correlating BET surface area, pore size, surface chemistry, and colloidal stability with adsorption performance, silica-based hybrids can be rationally designed for efficient removal of complex dye mixtures [59].

6.0 PROCESS OPTIMIZATION, REGENERATION, AND PRACTICAL APPLICATIONS

6.1 Process Optimization Strategies

6.1.1 Response Surface Methodology and Experimental Design

Response Surface Methodology (RSM) is the statistical method of choice for optimizing adsorption processes involving silica-based hybrid materials, with central composite design and Box–Behnken Design (BBD) being the most widely applied for evaluating main and interaction effects of process variables [60]. Optimization typically considers parameters such as pH, contact time, adsorbent dosage, initial dye concentration, and temperature, which are frequently modeled using RSM or BBD [60]. Under optimized conditions, removal efficiencies exceeding 90% have been achieved for a range of dye pollutants. Dosage optimization by RSM has identified effective concentrations of 0.1–0.5 g/L for achieving >90% removal, as demonstrated in studies of chitosan–silica hybrids applied to azo dyes [61].

6.1.2 Critical Process Parameters and Advanced Optimization

Key optimization parameters include pH (3–10), which is a critical determinant of dye uptake. Anionic dyes exhibit maximum adsorption under acidic conditions (pH 2–4) on positively charged hybrids, whereas cationic dyes show higher affinity in alkaline media (pH 8–10) [62]. For multi-dye mixtures, optimization accounts for competitive interactions, achieving up to 95% removal at an optimized pH of 7. Contact time ranges from 5–900 minutes, with equilibrium typically reached within 30–120 minutes, well described by pseudo-second-order kinetics; in multi-dye systems, optimal contact time is about 80 minutes. Adsorbent dosage usually falls within 0.1–2.0 g/L, with initial pollutant concentrations spanning 10–500 mg/L [61]. Temperature optimization generally covers 15–45 °C, though adsorption is exothermic in most systems, leading to reduced capacities above 40 °C [61]. Multi-objective optimization approaches incorporate multiple performance criteria, such as removal efficiency, cost-effectiveness, and environmental impact, with Pareto-optimal solutions balancing competing objectives, including maximum removal capacity and minimum adsorbent dosage [61]. Machine learning techniques, particularly artificial neural networks and genetic algorithms, are increasingly applied for predicting and optimizing adsorption in complex systems, enabling real-time process control and adaptive optimization under varying wastewater characteristics [63].

6.1.3 Process Intensification and Scale-up

Continuous processes provide distinct advantages over batch operations, particularly in processing capacity and operational flexibility. Data from fixed-bed column studies are widely employed to evaluate breakthrough behavior and to inform scale-up calculations for industrial applications. Fluidized bed reactors further enhance mass transfer while minimizing pressure drop compared to packed-bed configurations, and hybrid approaches that integrate adsorption with photocatalysis or membrane separation demonstrate synergistic effects that significantly improve overall treatment performance [64].

Scaling up from laboratory (mL) to pilot (L) and industrial (m^3) levels, however, presents substantial technical and economic challenges. At larger scales, mixing effects become increasingly critical, with Damköhler numbers exerting a strong influence on product quality and consistency [65]. In industrial-scale synthesis, the energy-intensive requirements of mixing often constitute a major component of operational costs [65]. Nevertheless, continuous manufacturing strategies employing continuous stirred-tank reactors and plug flow reactors offer superior scalability and cost-effectiveness relative to conventional batch processes.

6.2 Regeneration and Reusability

6.2.1 Desorption Mechanisms and Strategies

Regeneration strategies are determined by the type of adsorbate–adsorbent interaction, with different approaches required for physisorbed and chemisorbed pollutants. Common desorbents include NaOH, HCl, and ethanol. Chemical desorption using acid or base solutions enables selective recovery of pollutants while maintaining adsorbent integrity, as demonstrated by ZnO-functionalized SBA-15 regenerated with 0.1 M NaOH and cellulose–silica beads effectively regenerated through acid desorption [66, 67].

Thermal desorption in the range of 80–120 °C is effective for most organic pollutants, with energy demands between 2.55 and 26.50 kJ/mmol depending on material properties. Regeneration at approximately 200 °C is particularly suitable for chitosan–fumed silica systems, as it preserves their structural stability [68]. Solvent extraction provides comparatively mild regeneration conditions, although solvent recovery is necessary for sustainable application.

6.2.2 Cyclic Performance and Material Stability

Long-term stability studies demonstrate that well-designed silica-based hybrid materials can retain more than 70% of their initial adsorption capacity after 10 consecutive cycles, with most hybrids maintaining 80–95% capacity over 4–6 cycles. Specific performance comparisons show that ZnO-functionalized SBA-15 preserves 85% efficiency after 5 cycles, while cellulose–silica beads maintain 90% retention after 4 cycles [69]. Regeneration efficiency generally declines by 5–15% per cycle due to incomplete desorption and gradual structural changes, with multi-cycle tests indicating progressive capacity loss from site blockage that can be mitigated by hybrid stability [33]. The economic feasibility of regeneration processes requires achieving more than 80% capacity retention over at least 5–10 cycles [33].

Common degradation mechanisms include cleavage of organic groups, pore structure collapse, and particle aggregation, which can be reduced through mild regeneration conditions ($T < 100$ °C, neutral pH) to prolong material lifetime [64]. Protective modifications such as crosslinking and encapsulation enhance stability under harsh regeneration conditions, while advanced magnetic-core hybrids enable easier separation and recovery, thereby reducing mechanical stress during regeneration [67]. Real-time monitoring of key performance indicators supports predictive maintenance and facilitates optimal regeneration scheduling.

6.3 Industrial and Practical Applications

6.3.1 Real-World Treatment Systems and Integration

Textile industry applications demonstrate effective treatment of multi-component dye effluents, achieving >95% removal efficiency through both batch and column systems, with hybrids such as polyaniline–silica nanocomposites removing 90% of dyes at pilot scale [70]. Pharmaceutical wastewater treatment enables selective removal of active compounds without interference from other components, while recovery of heavy metals from mining and electroplating wastewaters supports both environmental protection and resource recovery [66].

Hybrids integrate efficiently with coagulation or photocatalysis, attaining >95% COD reduction, and coupling silica-based adsorbents with membrane bioreactor systems enhances pollutant removal while reducing fouling [71]. Retrofit applications in existing treatment facilities demonstrate compatibility with conventional processes, whereas point-of-use applications for drinking water provide decentralized solutions for emerging contaminant removal. Broader environmental and agricultural applications include soil remediation through in-situ treatment using silica-based materials, treatment of agricultural runoff to prevent eutrophication and protect water resources, and groundwater remediation employing permeable reactive barriers containing functionalized silica hybrids [72].

6.3.2 Economic and Environmental Considerations

Techno-economic analysis demonstrates that silica-based hybrid adsorbents are cost-competitive with conventional treatment processes, with low-cost hybrids derived from waste materials such as bagasse ash showing particular promise for industrial application, as evidenced by field trials achieving 85% multi-dye removal [73]. Capital expenditure comprises synthesis equipment, characterization facilities, and downstream processing units, while operating expenditure includes raw materials, energy, labor, and waste management [74].

Life cycle cost analysis indicates that high-performance materials justify higher prices through superior efficiency and extended operational lifetime. Life Cycle Assessment studies reveal that silica precursor selection contributes 69–100% of total emissions, while bioinspired synthesis pathways reduce energy consumption by up to 95% compared to conventional high-temperature routes [75]. Reported carbon footprints range from 0.01 to 0.9 kg CO_2e/kg depending on synthesis and purification methods, with post-treatment toxicity reduction confirmed through bioassays meeting EPA standards [76]. Incorporating circular economy principles, such as recycling and waste valorization, further minimizes environmental impact.

6.4 Future Perspectives and Emerging Trends

pH-responsive and temperature-sensitive functionalization enables triggered release and enhanced selectivity, while magnetic separation ensures efficient recovery and regeneration in industrial processes. Photocatalytic hybrid systems integrate adsorption with in-situ pollutant degradation, resulting in improved treatment efficiency [77]. Real-time monitoring through IoT sensors allows adaptive process control and predictive maintenance, while artificial intelligence algorithms optimize operating conditions based on real-time performance data. Furthermore, digital twin technology supports virtual process optimization and reliable scale-up predictions. The use of bio-based precursors and green synthesis strategies reduces both environmental impact and production costs, waste valorization practices convert industrial by-products into high-performance adsorbent materials, and closed-loop systems minimize waste generation while maximizing resource utilization efficiency [78].

7. CONCLUSION

This review has demonstrated that silica-based hybrid adsorbents hold strong potential as efficient and sustainable materials for the removal of multiple dyes from wastewater. Their high surface area, tunable porosity, and versatile functionalization address the shortcomings of conventional adsorbents, particularly under competitive adsorption conditions. By harnessing synergistic mechanisms such as π–π stacking, hydrogen bonding, and electrostatic interactions, these hybrids achieve enhanced selectivity and performance. Integrated approaches, including adsorption–photocatalysis, further expand their applicability by combining pollutant removal with in-situ degradation, thereby enabling simultaneous treatment and adsorbent regeneration within a single platform.

The sustainability and feasibility of these hybrids are reinforced by studies on regeneration capacity, process optimization, and life-cycle assessments. The use of bio-based precursors, waste valorization, and green synthesis strategies reduces production costs and environmental burdens, aligning the materials with circular economy principles. In addition, digital tools such as response surface methodology, artificial intelligence, and digital twin models create opportunities to optimize performance and scale-up with predictive accuracy. Collectively, these advancements position silica-based hybrids as cost-effective, durable, and environmentally responsible technologies for wastewater treatment.

Silica-based hybrids directly address the challenges of industrial dye pollution by combining efficiency, selectivity, and compatibility with existing treatment systems. Their implementation not only reduces environmental and public health risks but also advances sustainability targets by minimizing energy requirements and secondary waste generation. Bridging laboratory innovation with industrial application will require pilot-scale demonstrations, regulatory incentives, and strong industry–academic partnerships. Strategic investment in this transition would position the United States as a global leader in next-generation wastewater treatment technologies, safeguarding water resources and reinforcing its commitment to sustainable environmental management.

REFERENCES

1. *Singh, B.J., A. Chakraborty, and R. Sehgal, A systematic review of industrial wastewater management: Evaluating challenges and enablers. Journal of Environmental Management, 2023. 348: p. 119230.*
2. *Morrison, J., OVERSIGHT EPA taken to task on hazardous chemicals discharged to waterways. 2014, AMER CHEMICAL SOC 1155 16TH ST, NW, WASHINGTON, DC 20036 USA.*
3. *Periyasamy, A.P., Recent advances in the remediation of textile-dye-containing wastewater: prioritizing human health and sustainable wastewater treatment. Sustainability, 2024. 16(2): p. 495.*
4. *Morris, J.C., Planning for water infrastructure: Challenges and opportunities. Public Works Management & Policy, 2017. 22(1): p. 24-30.*
5. *Singh, K. and S. Arora, Removal of synthetic textile dyes from wastewaters: a critical review on present treatment technologies. Critical reviews in environmental science and technology, 2011. 41(9): p. 807-878.*
6. *Carmen, Z. and S. Daniela, Textile organic dyes-characteristics, polluting effects and separation/elimination procedures from industrial effluents-a critical overview. Vol. 3. 2012: IntechOpen Rijeka.*
7. *Khan, W.U., et al., A critical review of hazardous waste generation from textile industries and associated ecological impacts. Journal of the Indian Chemical Society, 2023. 100(1): p. 100829.*
8. *Saravanakumar, K., et al., Impact of industrial effluents on the environment and human health and their remediation using MOFs-based hybrid membrane filtration techniques. Chemosphere, 2022. 307: p. 135593.*
9. *Satyam, S. and S. Patra, Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review. Heliyon, 2024. 10(9).*
10. *Nayl, A., et al., Recent progress in the applications of silica-based nanoparticles. RSC advances, 2022. 12(22): p. 13706-13726.*
11. *Dey, S., et al., Engineered mesoporous silica: a robust solution for inorganic and organic pollutant removal from water. Environmental Monitoring and Assessment, 2025. 197(4): p. 1-27.*
12. *Al-Amrani, W.A., M.A.K.M. Hanafiah, and A.-H.A. Mohammed, A comprehensive review of anionic azo dyes adsorption on surface-functionalised silicas. Environmental Science and Pollution Research, 2022. 29(51): p. 76565-76610.*
13. *Xia, K., et al., Synthesis of hybrid silica materials with tunable pore structures and morphology and their application for heavy metal removal from drinking water. Journal of Hazardous Materials, 2010. 183(1-3): p. 554-564.*
14. *Tiwari, I. and P. Mahanwar, Polyacrylate/silica hybrid materials: A step towards multifunctional properties. Journal of Dispersion Science and Technology, 2019. 40(7): p. 925-957.*
15. *Grisolia, A., et al., Hybrid Polymer-Silica Nanostructured Materials for Environmental Remediation. Molecules, 2023. 28(13).*
16. *Bachvarova-Nedelcheva, A., et al., Sol-Gel Synthesis of Silica-Poly (Vinylpyrrolidone) Hybrids with Prooxidant Activity and Antibacterial Properties. Molecules, 2024. 29(11).*
17. *Zhang, L., et al., Templated Growth of Crystalline Mesoporous Materials: From Soft/Hard Templates to Colloidal Templates. Front Chem, 2019. 7: p. 22.*
18. *Moura, H.M., H. Peterlik, and M.M. Unterlass, Green hydrothermal synthesis yields perylenebisimide–SiO 2 hybrid materials with solution-like fluorescence and photoredox activity. Journal of Materials Chemistry A, 2022. 10(24): p. 12817-12831.*
19. *Gong, S.-q., et al., Synthesis of antimicrobial silsesquioxane–silica hybrids by hydrolytic co-condensation of alkoxysilanes. Polymer Chemistry, 2014. 5(2): p. 454-462.*
20. *Chen, F., et al., Organosilica nanoparticles with an intrinsic secondary amine: an efficient and reusable adsorbent for dyes. ACS applied materials & interfaces, 2017. 9(18): p. 15566-15576.*
21. *Yin, X., et al., Review on Synthesis of Silica-Based Hybrid Sorbents and Their Application in Radionuclide Separation and Removal via Chromatographic Technique. Toxics, 2025. 13(4): p. 319.*
22. *Parida, D., et al., Template-free synthesis of hybrid silica nanoparticle with functionalized mesostructure for efficient methylene blue removal. Materials & Design, 2021. 201: p. 109494.*
23. *Jung, C.Y., et al., One-step synthesis of structurally controlled silicate particles from sodium silicates using a simple precipitation process. Langmuir, 2010. 26(8): p. 5456-5461.*
24. *Hassan, M.M. and C.M. Carr, Biomass-derived porous carbonaceous materials and their composites as adsorbents for cationic and anionic dyes: A review. Chemosphere, 2021. 265: p. 129087.*
25. *Amrutha, et al., Multi-component adsorption isotherms: review and modeling studies. Environmental processes, 2023. 10(2): p. 38.*
26. *Girish, C., Multicomponent adsorption and the interaction between the adsorbent and the adsorbate: A review. interaction, 2018. 14: p. 15.*
27. *Van Assche, T.R., G.V. Baron, and J.F. Denayer, An explicit multicomponent adsorption isotherm model: accounting for the size-effect for components with Langmuir adsorption behavior. Adsorption, 2018. 24(6): p. 517-530.*
28. *Ng, K.C., et al., A universal isotherm model to capture adsorption uptake and energy distribution of porous heterogeneous surface. Scientific Reports, 2017. 7(1): p. 10634.*
29. *Landa, H.O.R., D. Flockerzi, and A. Seidel-Morgenstern, A method for efficiently solving the IAST equations with an application to adsorber dynamics. AIChE Journal, 2013. 59(4): p. 1263-1277.*
30. *Acharya, A., et al., Development of a multicomponent adsorption isotherm equation and its validation by modeling. Langmuir, 2023. 39(49): p. 17862-17878.*

31. *Yin, C., et al., Competitive adsorption behavior and adsorption mechanism of limestone and activated carbon in polymetallic acid mine water treatment. Scientific Reports, 2024. 14(1): p. 23561.*
32. *Kouzoutzoglou-Efremidou, A.A., et al., Interfacial adsorption interactions of dyes and chitosan/activated carbon@ curcumin derivatives in single-component and binary solutions. Langmuir, 2025. 41(5): p. 3603-3622.*
33. *Abdulazeez, I., et al., Facile engineering of mesoporous silica for the effective removal of anionic dyes from wastewater: Insights from DFT and experimental studies. Heliyon, 2023. 9(11): p. e21356.*
34. *Yue, Y., et al., Synergistic adsorption and photocatalysis study of TiO(2) and activated carbon composite. Heliyon, 2024. 10(10): p. e30817.*
35. *de Menezes, E.W., et al., Ionic silica based hybrid material containing the pyridinium group used as an adsorbent for textile dye. Journal of colloid and interface science, 2012. 378(1): p. 10-20.*
36. *Camparotto, N.G., et al., Synergistic effect in simultaneous adsorption of cationic and anionic emerging contaminants by chitosan aerogels containing nanocellulose-modified tannic acid. Journal of Water Process Engineering, 2023. 53: p. 103749.*
37. *Dhaneswara, D., et al., Synthesis of Mesoporous Silica from Sugarcane Bagasse as Adsorbent for Colorants Using Cationic and Non-Ionic Surfactants. International Journal of Technology, 2024. 15(2).*
38. *Wu, Q., et al., Synergistically enhancing the selective adsorption of cationic dyes through copper impregnation and amino functionality into iron-based metal-organic frameworks. Science of the Total Environment, 2024. 923: p. 171280.*
39. *Salehifar, N., et al., Calculations of adsorption-dependent refractive indices of metal-organic frameworks for gas sensing applications. Opt Express, 2023. 31(5): p. 7947-7965.*
40. *Chen, H., et al., XPS and two-dimensional FTIR correlation analysis on the binding characteristics of humic acid onto kaolinite surface. Science of the Total Environment, 2020. 724: p. 138154.*
41. *Lu, S., et al., Recent developments and challenges for volatile organic compounds control by the synergistic of adsorption and photocatalysis. Applied Catalysis O: Open, 2024. 193: p. 206975.*
42. *Aruna Janani, V., et al., Optimization studies on methyl orange (MO) dye adsorption using activated carbon nanoadsorbent of ocimum basilicum linn leaves. Journal of Nanomaterials, 2023. 2023(1): p. 7969512.*
43. *Manjunath, S., R.S. Baghel, and M. Kumar, Antagonistic and synergistic analysis of antibiotic adsorption on Prosopis juliflora activated carbon in multicomponent systems. Chemical Engineering Journal, 2020. 381: p. 122713.*
44. *Cheng, L., et al., Synergistic adsorption-photocatalysis for dyes removal by a novel biochar–based Z-scheme heterojunction BC/2ZIS/WO3: Mechanistic investigation and degradation pathways. Chemical Engineering Journal, 2022. 445: p. 136677.*
45. *Rangelova, N., et al., Methylcellulose/SiO2 hybrids: sol-gel preparation and characterization by XRD, FTIR and AFM. Central European Journal of Chemistry, 2011. 9(1): p. 112-118.*
46. *Khanh Nguyen, Q.N., et al., Synthesis and characterization of mesoporous silica SBA-15 and ZnO/SBA-15 photocatalytic materials from the ash of brickyards. Journal of Chemistry, 2020. 2020(1): p. 8456194.*
47. *Mascotto, S., et al., Analysis of microporosity in ordered mesoporous hierarchically structured silica by combining physisorption with in situ small-angle scattering (SAXS and SANS). Langmuir, 2009. 25(21): p. 12670-12681.*
48. *Putz, A.M., et al., Comparison of Structure and Adsorption Properties of Mesoporous Silica Functionalized with Aminopropyl Groups by the Co-Condensation and the Post Grafting Methods. Materials (Basel), 2021. 14(3).*
49. *Wang, X., et al., Synthesis of ordered mesoporous silica with tunable morphologies and pore sizes via a nonpolar solvent-assisted stober method. Chemistry of Materials, 2016. 28(7): p. 2356-2362.*
50. *Rehman, F., P.L. Volpe, and C. Airoldi, Free amino and imino-bridged centres attached to organic chains bonded to structurally ordered silica for dye removal from aqueous solution. Journal of environmental management, 2014. 133: p. 135-143.*
51. *Luan, P. and G.S. Oehrlein, Characterization of ultrathin polymer films using p-polarized ATR-FTIR and its comparison with XPS. Langmuir, 2019. 35(12): p. 4270-4277.*
52. *Diosa, J., et al., Modeling surface chemistry and adsorption behavior of biomimetic chitosan/silica hybrid materials. Journal of Materials Research and Technology, 2020. 9(4): p. 8092-8103.*
53. *Beurer, A.-K., et al., Comparative study of lattice parameter and pore size of ordered mesoporous silica materials using physisorption, SAXS measurements and transmission electron microscopy. Microporous and Mesoporous Materials, 2023. 354: p. 112508.*
54. *Muchan, P., C. Saiwan, and M. Nithitanakul, Investigation of adsorption/desorption performance by aminopropyltriethoxysilane grafted onto different mesoporous silica for post-combustion CO2 capture. Clean Energy, 2020. 4(2): p. 120-131.*
55. *Dhawade, P. and R. Jagtap, Comparative study of physical and thermal properties of chitosan-silica hybrid coatings prepared by sol-gel method. Chem. Sin, 2012. 3(3): p. 589-601.*
56. *Carvalho, P.M., et al., Application of light scattering techniques to nanoparticle characterization and development. Frontiers in chemistry, 2018. 6: p. 237.*
57. *Wu, Y., et al., Functionalized mesoporous silica material and anionic dye adsorption: MCM-41 incorporated with amine groups for competitive adsorption of Acid Fuchsine and Acid Orange II. RSC Advances, 2014. 4(106): p. 61256-61267.*
58. *Hou, Z., et al., Hierarchically porous carbon derived from pore remodeling of waste polymeric membranes for high-efficiency adsorption applications. Resources, Conservation and Recycling, 2023. 190: p. 106845.*
59. *Huang, P., et al., Dye-mediated interactions in chitosan-based polyelectrolyte/organoclay hybrids for enhanced adsorption of industrial dyes. ACS applied materials & interfaces, 2019. 11(12): p. 11961-11969.*

60. *Ravikumar, K., et al., Optimization of process variables by the application of response surface methodology for dye removal using a novel adsorbent. Dyes and Pigments, 2007. 72(1): p. 66-74.*
61. *Obayomi, K.S., et al., A response surface methodology approach for the removal of methylene blue dye from wastewater using sustainable and cost-effective adsorbent. Process Safety and Environmental Protection, 2024. 184: p. 129-150.*
62. *Attallah, O.A., et al., Removal of cationic and anionic dyes from aqueous solution with magnetite/pectin and magnetite/silica/pectin hybrid nanocomposites: kinetic, isotherm and mechanism analysis. RSC advances, 2016. 6(14): p. 11461-11480.*
63. *Subraveti, S.G., et al., Machine learning-based multiobjective optimization of pressure swing adsorption. Industrial & Engineering Chemistry Research, 2019. 58(44): p. 20412-20422.*
64. *Al-Amrani, W.A., A.A. Mohammed, and M.A.K.M. Hanafiah, Breaking the Batch Barrier: Magnetic Silica Gel Fixed-Bed Columns for Sustainable Acid Orange 10 Removal-Optimization, Regeneration, and Cost Analysis. Next Research, 2025: p. 100652.*
65. *Takors, R., How can we ensure the successful transfer from lab‐to large‐scale production? 2016, Wiley Online Library. p. 587-587.*
66. *Alsawy, T., et al., A comprehensive review on the chemical regeneration of biochar adsorbent for sustainable wastewater treatment. NPJ Clean Water, 2022. 5(1): p. 29.*
67. *Omorogie, M.O., J.O. Babalola, and E.I. Unuabonah, Regeneration strategies for spent solid matrices used in adsorption of organic pollutants from surface water: a critical review. Desalination and water treatment, 2016. 57(2): p. 518-544.*
68. *Oesterle, P., Exploring the fate of emerging contaminants during hydrothermal regeneration of carbonaceous adsorbents. 2023, Umeå University.*
69. *Zaharia, C., C.-P. Musteret, and M.-A. Afrasinei, The use of coagulation–flocculation for industrial colored wastewater treatment—(I) the application of hybrid materials. Applied Sciences, 2024. 14(5): p. 2184.*
70. *Khan, M., et al., Applications of polyaniline-impregnated silica gel-based nanocomposites in wastewater treatment as an efficient adsorbent of some important organic dyes. Green Processing and Synthesis, 2022. 11(1): p. 617-630.*
71. *Januário, E.F.D., et al., Performance of a hybrid coagulation/flocculation process followed by modified microfiltration membranes for the removal of solophenyl blue dye. Chemical engineering and processing-process intensification, 2021. 168: p. 108577.*
72. *Salman, M., et al., Recent advances in the application of silica nanostructures for highly improved water treatment: a review. Environmental Science and Pollution Research, 2019. 26(21): p. 21065-21084.*
73. *Naseem, T., et al., Mesoporous silica prepared via a green route: a comparative study for the removal of crystal violet from wastewater. Materials Research Express, 2020. 8(1): p. 015005.*
74. *Moya, J.A. and A. Boulamanti, Production costs from energy-intensive industries in the EU and third countries. Publications Office of the European Union: Luxembourg, 2016.*
75. *Gu, S., et al., Life cycle assessment and process optimization of precipitated nanosilica—A case study in China. Energies, 2024. 17(22): p. 5621.*
76. *Sævarsdottir, G., H. Kvande, and T. Magnusson. Greenhouse gas emissions from silicon production-development of carbon footprint with changing energy systems. in Proceedings of the 16th International Ferro-Alloys Congress (INFACON XVI). 2021.*
77. *Ortiz-Bustos, J., et al., Tuning adsorption capacities of hybrid mesoporous silica nanospheres and adsorption mechanism study for sulfamethoxazole and diclofenac removal from water. Journal of Molecular Liquids, 2024. 398: p. 124213.*
78. *Wang, W. and A. Wang, Perspectives on green fabrication and sustainable utilization of adsorption materials for wastewater treatment.* Chemical Engineering Research and Design, 2022. **187**: p. 541-548.