

From Pristine to Composite: Nano-alumina as a Versatile Adsorbent for Dye Removal in Water Treatment

Masoud Saadati*

Department of Chemistry, Farhangian University, Tehran, Iran

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Corresponding Authors:

Masoud Saadati

Email:

m.saadati@cfu.ac.ir

ABSTRACT

Wastewater from textile and dyeing industries releases large amounts of synthetic dyes into the environment, creating serious ecological and health problems. This review begins with the idea that alumina-based nanomaterials (NMs) can be designed to improve dye removal from polluted water. To examine this idea, published studies were collected, compared, and grouped based on how the materials were made, how they work during adsorption, and how well they remove dyes. The reviewed research was organized into main areas including natural adsorption abilities of pristine NMs, improved adsorption through surface modification and added functional groups, alumina-based nanocomposites combined with metals, polymers, or carbon materials, nano-alumina used in membranes, and new hybrid adsorbents. The comparison shows that unmodified nano-alumina has moderate dye removal ability, mainly due to its surface hydroxyl groups and electrostatic interactions. However, when alumina is modified - through functionalization, doping, or forming composites - its adsorption capacity, selectivity, stability, and reusability increase significantly. Overall, the findings support the initial idea that engineered alumina-based nanomaterials are promising tools for advanced dye removal. This review provides a clear summary of current progress and highlights important research needs for developing more effective and sustainable water-treatment technologies.

KEYWORDS: Nano-alumina; Nanocomposites; Dyes removal; Nanoadsorbent; Water treatment

1. Introduction

Water pollution is a critical global challenge with significant consequences for the ecology and health of living beings and humans. It arises from multiple human-caused sources, including industrial effluents, agricultural wastewater, and inadequate waste management practices. Addressing these issues requires implementing advanced wastewater treatment technologies to increase pollutant removal [1]. The widespread use of synthetic dyes in various sectors, including textiles, dyeing and printing, leather tanning, paints, paper and pulp, cosmetics, food processing, dye manufacturing, and pharmaceuticals, has substantially contributed to this issue. The textile industry contributes significantly to this pollution due to its high-water consumption and the import of wastewater

containing dyes [2]. Today, the use of dyes in textile production continues to increase, resulting in large volumes of dye-containing wastewater discharged into the environment [3].

Synthetic dyes, which include anionic (acid), cationic (basic), and non-ionic (disperse) types, are chemically complex and resistant to biodegradation. These dyes are often toxic, carcinogenic, and can cause serious harm to humans and aquatic life, affecting organs like the kidneys, liver, and brain [4]. Dyes contain molecular structures like chromophores, conjugated systems, and auxochromes that impart color and improve solubility. Many dyes contain toxic metals (e.g., cadmium, lead, chromium) and are produced using hazardous chemicals [2]. The textile industry is responsible for approximately



20% of the global water pollution problem. The presence of dyes in food chains, such as in fish, has been demonstrated to exert a significant impact on both aquatic ecosystems and human health [5]. Therefore, it is very important to develop and use eco-friendly technologies to treat contaminated water. This will help reduce the harmful impacts on the environment and human health.

There are many ways to remove dyes from water, such as electrolysis, biodegradation, and photocatalytic degradation. However, these methods often cost a lot, don't work well, or create more pollutants. Because of this, they are not considered practical for use in small- and medium-sized industries [2]. On the other hand, synthetic dyes present a challenge to conventional methods of elimination due to their chemical stability and toxicity. Adsorption is a well-known method for dye removal. It is simple, cost-effective, efficient, and environmentally friendly. Although adsorption has been used for many years, interest in nanostructured materials has increased because recent studies show that nanomaterials can significantly improve the treatment of dye-polluted wastewater due to their large surface area, tunable structure, and good activity under visible light [6]. For example, the $\text{ErVO}_4/\text{g-C}_3\text{N}_4$ photocatalyst shows how combining two nanomaterials can improve charge separation and increase the breakdown of dyes under light [7]. In another study, TmVO_4 nanoparticles were prepared through an easy auto-combustion method, and careful control of the starting materials and conditions produced stable particles that were able to degrade different dyes with good reuse performance [8]. Similarly, another work used a fast sonochemical method to make silver tungstate nanoparticles, which showed very high activity in removing several dyes and organic pollutants under visible light and maintained their performance after repeated use [9]. These works together show that improving the design, structure, and preparation of nanomaterials can strongly enhance dye removal, highlighting their importance in modern water treatment. Nanoadsorbents, including alumina-based ones, are a great way to clean up textile dye pollution, and this highlights why it is important to study alumina-based materials more closely [10].

Numerous studies have reviewed various aspects of water treatment. Most of these reviews have focused either on the use of different adsorbents for dye removal from wastewater [5,11–12] or on

the application of nano-alumina for the treatment of a broad range of pollutants [4,10,13]. The present review provides the first comprehensive analysis dedicated exclusively to dye removal from wastewater using alumina-based nanoadsorbents, without considering other adsorbents or target analytes. The collected studies are organized into several main subsections: alumina's edge in nanomaterial adsorption, pristine Al_2O_3 nanoparticles (NPs) in dye decontamination, enhanced dye adsorption via surface-modification and functionalization of nano-alumina, alumina-based nanocomposites and, nano-alumina based membranes and innovative adsorbents for dye removal. We have included relevant publications in this review when we could find them. The review is organized so that it shows how research advancements happened over time. It highlights important developments and distinctive characteristics of each study or period in a way that is easy for readers to understand. Also, a summary of the basic features of each dye removal method is included. The discussion of alumina synthesis methods is reserved exclusively for those methods that represent innovative approaches.

2. Alumina: A nanoadsorbent standout

Nanomaterials (NMs) are substances that are between 1 and 100 nanometers long in at least one-dimension. They must also have a specific surface area greater than $60 \text{ m}^2/\text{cm}^3$ when expressed as spherical surface area per unit volume [14]. At the nanoscale, the reduction in particle size leads to a significant increase in surface area and surface energy. This, in turn, enhances adsorption capacity due to the abundance of active surface atoms. These atoms often have an unsaturated structure, which makes them highly reactive with metal ions and polar compounds. This property makes NMs highly effective adsorbents [15].

The main classes of NMs are: Carbon-based NMs (include fullerenes, carbon nanotubes, and graphene), metallic NMs (are made from metals like silver, copper, iron, and zinc), dendrimers (a type of molecule that has a branching structure and are very small, measuring in nanometers), nanocomposites (are materials composed of a matrix embedded with nanoscale fillers to enhance mechanical, thermal, or functional properties), and quantum dots (tiny particles that have special properties because of their size). Broad chemical classifications include metals, metal oxides, bimetallics, carbon-based

materials, zeolites, silica, ceramics, semiconductors, polymers, lipids, and metal-organic frameworks [6]. Aluminum oxide (alumina) nanostructures, a type of metal oxide, show great potential as solid-phase adsorbents due to their high surface area and adsorption capacity, mechanical robustness, lower regeneration temperature requirements, ion-exchange capabilities and ease of regeneration [10]. Various alumina nanostructures, such as activated alumina, mesoporous alumina, spherical hollow nanostructures, nanowires, nanotubes, nanofibers, anodic porous alumina, and nanocomposites, have been studied for their ability to adsorb heavy metals, nitrates, fluorides, dyes, carbon dioxide, radioactive substances, and organic contaminants [16].

The synthesis of alumina can be achieved through various methodologies, including sol-gel, combustion, precipitation, microwave, and hydrothermal techniques [10]. Alumina (Al_2O_3) exists in different forms depending on how it's made. Each form has unique structural and functional characteristics, determined by the conditions used during synthesis. The α -phase is typically obtained by high-temperature calcination (above 1100°C) of transitional alumina and stable and doesn't break down at temperatures above 1000°C . It has a hexagonal crystal structure. The γ -phase, which is usually synthesized via low-temperature methods such as precipitation or sol-gel followed by calcination around $400\text{--}600^\circ\text{C}$, has a faulty spinel lattice with empty spaces for positive ions. This makes it better at capturing pollutants that have a positive charge. Other structural forms include $\beta\text{-Al}_2\text{O}_3$, a mixed oxide doped with Na^+ and Mg^{2+} ions, which is known for its high ionic conductivity and applications in solid-state electrolytes, and can be synthesized by controlled hydrothermal treatment of aluminum hydroxide under specific pH and temperature conditions, often followed by mild calcination. Amphoteric hydroxides exhibit pH-dependent adsorption and ion-exchange properties. Aluminum phosphates and zeolites, which are made by heating up water, have been shown to separate molecules and exchange ions [17]. Although this article does not focus on the classification of nano-alumina based on their morphology, it is important to note that these materials can be organized into one-, two-, and three-dimensional forms. Each dimensional type has distinct structural features, physicochemical properties, and synthesis methods, which lead to

different advantages in various applications [18]. Collectively, these diverse alumina structures exhibit versatile physicochemical properties - such as surface adsorption, ion exchange, molecular exclusion, and complexation - making them highly promising for advanced water purification technologies.

3. The Alumina advantage in dye adsorption

3.1. Pristine Al_2O_3 NPs in dye decontamination

Alumina NPs are widely studied for removing dyes from wastewater. Their adsorption process typically involves physical adsorption and electrostatic attraction between the dye molecules and alumina surface sites. In one of the early studies, nano-alumina, a non-carbon waste-derived adsorbent, was utilized for the removal of the azo dye, Tropaeoline 000, from wastewater samples. Adsorption equilibrium isotherms were experimentally determined at various temperatures and analyzed using Freundlich and Langmuir models to extract characteristic parameters. Preliminary kinetic studies indicated that the adsorption process followed a pseudo-second-order model. The thermodynamic parameters calculated from the Langmuir constants confirm the spontaneous and favorable nature of the adsorption process. These findings underscore the potential of nano-alumina as an effective adsorbent for wastewater treatment applications [19]. Acid Red 18 (AR18), an azo dye frequently utilized in the textile and dyeing industries, poses considerable environmental and health hazards due to its toxic and potentially carcinogenic nature. A study performed a few years ago sought to evaluate the efficiency of nano-alumina for the removal of AR18 from aqueous solutions. Nano-alumina has been demonstrated to possess considerable potential as an effective adsorbent for the removal of AR18 from aqueous solutions, particularly under acidic conditions [20]. The adsorption behavior of Reactive Red 120 (RR120) dye from aqueous solutions using nano-alumina as an adsorbent was also systematically investigated through batch experiments. The maximum removal efficiency was achieved at an acidic pHs. An increase in adsorbent dose enhanced dye removal efficiency but led to a decrease in adsorption capacity, indicating potential site saturation maybe due to monolayer adsorption [21].

A novel and eco-friendly strategy for sludge

recycling was developed, involving a one-step high-temperature calcination process that converted electrocoagulation sludge into crystalline metal oxide NMs. The catalytic activity of the synthesized Al_2O_3 NMs was evaluated via the oxidative degradation of Basic Green 4 dye, demonstrating phase-dependent efficiency in environmental remediation processes [22]. Acid dyes, including Acid Red 14 (AR14), exhibit notable persistence and environmental hazards. To address this challenge, a study examined the adsorption efficacy of nano-alumina and micro-alumina powders in removing AR14 from aqueous solutions. The two adsorbents exhibited augmented removal efficiency and nano-alumina exhibited considerably higher adsorption capacity and efficiency in comparison to Micro-alumina, signifying its potential as an effective adsorbent for the elimination of acidic dyes from wastewater [23]. The adsorption of Congo Red (CR) dye onto alumina and nano-alumina has been the subject of study using a batch method. The findings indicated that nano-alumina exhibited more consistent and well-defined adsorption behavior in comparison to conventional alumina. Furthermore, nano-alumina exhibited enhanced sensitivity to temperature fluctuations and demonstrated a higher adsorption capacity, suggesting its superior performance in removing CR dye [24]. Orange G (OG), a monoazo dye commonly used in the textile and printing industries, has been identified as a carcinogenic and teratogenic compound, thereby constituting a substantial environmental and health hazard. γ -Alumina nanocrystals were synthesized and utilized for the adsorptive removal of this toxic anionic dye from aqueous solutions. The efficacy of the synthesized γ -alumina was further substantiated through its application to authentic industrial wastewater samples [25]. The elimination of RR-141, another azo dye linked to potential health risks, including allergic reactions and carcinogenicity, as well as environmental hazards to aquatic ecosystems, has also been investigated using γ - Al_2O_3 NPs [26].

The adsorption capacity of nanoalumina can be enhanced through the modification of synthesis conditions and the control of its chemical structure. A solvent-free hydrothermal-assisted calcination method was used to synthesize highly crystalline γ - Al_2O_3 NPs with a width of approximately 20 nanometers. The synthesis process was comprised of two primary stages of dehydration and calcination. The synthesized γ - Al_2O_3 exhibited robust selective

adsorption for anionic and cationic dyes. This selectivity is attributable to hydrogen bonding and electrostatic attraction between the dye and adsorbent. The study provides significant insights into the synthesis of crystalline γ - Al_2O_3 adsorbents, which possess the capacity for selective dye removal in wastewater treatment [27]. The employment of a novel homoleptic aluminum (III) derivative, designated as $[(\text{PhCOCHCOPh})_3\text{Al}]$, as a precursor in the synthesis of nano α -alumina, exhibited remarkable photocatalytic efficacy, achieving 95% photodegradation of CR dye under sunlight within a span of 10 minutes [28]. Furthermore, a novel sol-gel/flocculation method has been introduced for synthesizing α - Al_2O_3 NPs for the adsorptive and photocatalytic removal of Eriochrome Black T (EBT) under visible light. This method yielded several advantages e.g. resulting in a substantial enhancement in removal efficiency, from 14% to 93%. A synergistic adsorption/oxidation process under sunlight further degrades EBT. This process facilitates complete reuse of treated wastewater, underscoring its environmental and practical benefits [29]. A novel synthesis method of nano α - Al_2O_3 using the combustion method with aluminum salts as precursors and urea as the combustion agent followed by calcination has been reported. The produced NPs exhibited a remarkable adsorption capacity in removing methyl red (a model organic pollutant). These findings demonstrate the potential of combustion-synthesized Al_2O_3 NPs for advanced water purification and organic pollutant remediation [30].

A notable recent advancement in the synthesis of nano-alumina is the use of low-cost and readily available raw materials, and eco-friendly methods, representing a significant advantage of this nanomaterial. For instance, waste aluminum foil was employed as a precursor for the synthesis of alumina via a precipitation method. The synthesized alumina was subsequently applied for the removal of Reactive Green 19 (RG19) dye from simulated wastewater, achieving a maximum removal efficiency of 98.63%. The material exhibited a high specific surface area, as well as suitable pore volume and real and bulk densities [31]. A recent study has also demonstrated the efficacy of repurposing waste aluminum foils to synthesize nano- γ - Al_2O_3 , a material that has been shown to be highly effective in the removal of methylene blue (MB) from water (Fig. 1). The study's findings underscore the potential of nano- γ - Al_2O_3 , derived from aluminum

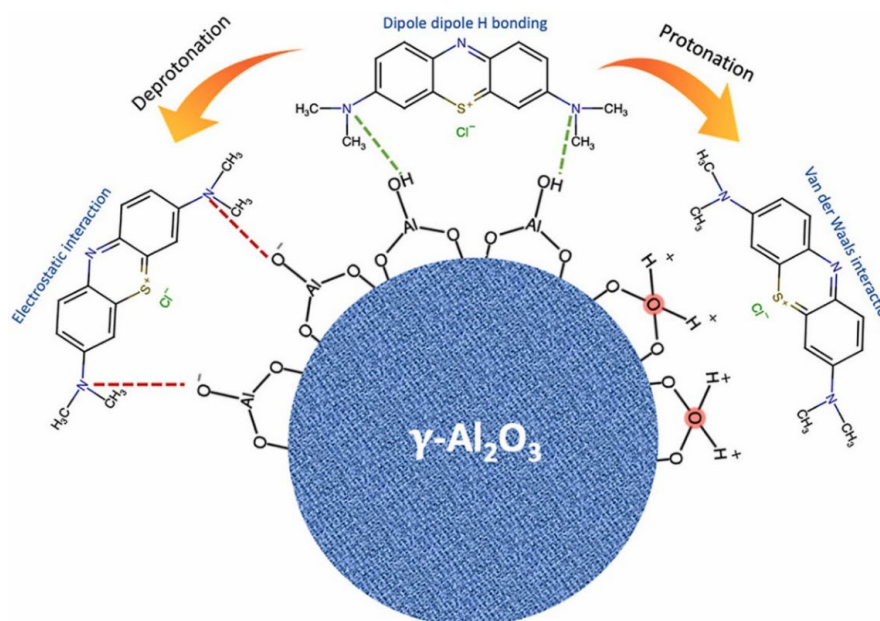


Fig. 1. Possible adsorption mechanisms of a dye onto nano- γ -Al₂O₃ [32]

waste, as a cost-effective and efficient adsorbent for dye remediation [32]. Furthermore, alumina NPs were synthesized from waste aluminum residue via an extraction and gel formation method and subsequently applied for the removal of Reactive Yellow 160 (RY160) dye from aqueous solutions. Characterization confirmed that the synthesized NPs consisted exclusively of aluminum and oxygen and exhibited a pure alumina crystalline phase at the nanoscale. These NPs demonstrated high adsorption efficiency for dye removal [33].

Utilizing an eco-friendly arc discharge technique that circumvents the use of toxic chemicals, the researchers accomplished the synthesis of alumina NPs in a single step, yielding particles that more closely resemble real-world NPs. Desorption tests demonstrated that the adsorbents could be efficiently regenerated and reused for up to five cycles. The two gamma and delta alumina phases that were synthesized in this method exhibited distinct mechanisms for MB dye removal. These mechanisms are attributed to the different lattice ion arrangements of the phases, which in turn influence their adsorption behavior [34].

A recently conducted study aims to evaluate the performance of nano γ -Al₂O₃, synthesized from low-cost kaolinitic clay, in removing Basic Blue 9 (BB9) dye from aqueous solutions. The objective of the present study was to determine whether the initial materials and synthesis methods exert

an influence on the efficiency of adsorption. The findings indicate that nano γ -Al₂O₃ possesses the potential to function as an effective adsorbent in the removal of BB9 from wastewater. This material offers a robust alternative to conventional materials in water treatment applications [35]. A new study has been offered a novel and cost-effective method for synthesizing Al₂O₃ NPs. This method utilizes Calligonum comosum leaf extract, resulting in Al₂O₃ NPs that are spherical, with an average crystallite size of 25.1 nm and an average particle size of 33 nm (Fig. 2). Photocatalytic tests demonstrated high degradation efficiencies for MB and Rose Bengal dyes [36].

Research findings demonstrate that alumina NPs effectively adsorb both anionic and cationic dyes, highlighting their promise for textile wastewater treatment [37]. Nano-alumina's advantages - including its high surface area, tunable crystal phases, rapid adsorption kinetics, selectivity, reusability, and cost-effective synthesis (even from waste-derived precursors) - position it as a versatile and sustainable material for removing diverse hazardous dyes via adsorption and photocatalysis.

3.2. Enhanced dye adsorption via surface-modified and functionalized nano-alumina

Despite its advantages, unmodified alumina NPs exhibit limited adsorption capacity for organic compounds, such as dyes, due to weak interactions

between the organic molecules and the hydrophilic alumina surface. This means that they can't remove organic contaminants as well as they should. In order to overcome this limitation, researchers have proposed that chemical or physical surface modification or functionalization of γ - Al_2O_3 NPs with specific functional groups is essential to enhance their adsorption performance [38]. The terms "surface modification" and "surface functionalization" of nano-alumina are closely related but differ in scope, purpose, and methods. It is imperative to delineate a scientific distinction in this regard. Surface modification of nano-alumina involves purposely altering its surface properties to enhance its performance in specific applications. This can be achieved through various physical or chemical techniques, either with or without the introduction of new chemical groups. The goal is to improve characteristics such as dispersion, adhesion, biocompatibility, and reactivity, making nano-alumina more versatile [39]. Surface functionalization of NPs refers to the modifying the chemical properties of their surface by introducing specific functional groups. (e.g., $-\text{NH}_2$, $-\text{COOH}$, $-\text{SH}$) by means of covalent or non-covalent interactions (Fig. 3). This process is necessary to adjust the physical and chemical properties of the NPs. This makes them more compatible and effective in specific uses, like biomedical

systems and catalytic processes [40]. Sometimes, when there is a need, these two tasks, surface modification and nanoparticle functionalization, are done simultaneously on alumina. These modifications aim to increase active sites, improve selectivity, and enable multifunctional mechanisms like photocatalytic degradation.

Sodium dodecyl sulfate (SDS) is a widely used surfactant in the field of nanomaterial modification, particularly in the context of dye removal processes involving nano-alumina. The material's ability to enhance the adsorption of dyes onto the alumina surface is well-documented, thereby increasing the efficiency of the removal process [41]. Its application in dye removal procedures has been an area of interest for numerous years. SDS surface modification neutralized the positive charge on the alumina and created a negatively charged layer, as evidenced by the shift in zeta potential from +41.2 mV to -40.5 mV. This change indicates that the dodecyl sulfate (DS^-) anions adsorbed onto the alumina surface, forming micelles that made a negative charge [42].

A simple, cost-effective, and sensitive solid-phase extraction method employing γ - Al_2O_3 NPs modified with SDS has been developed for the selective extraction, preconcentration, and detection of trace levels of malachite green (MG). The method proved effective when applied to fish

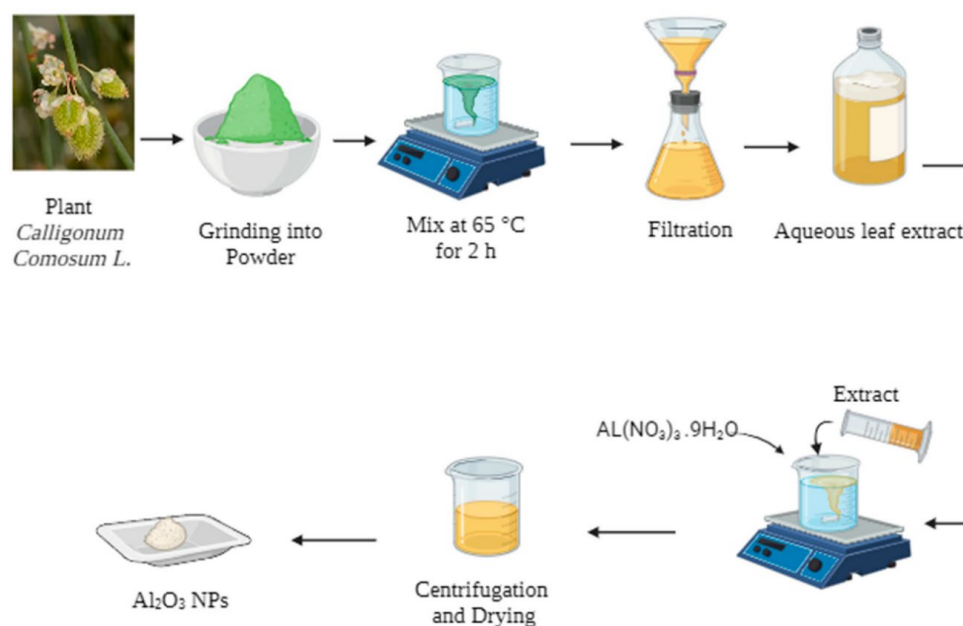


Fig. 2. A schematic illustrating the process of synthesizing Al_2O_3 NPs using an extract from the *Calligonum cosmosum* L. plant [36]

farming water samples, highlighting its practical utility and efficiency [43]. Although the utilization of alumina NPs that have undergone modification with SDS has been recognized in previous years [44], it remains in use today. In recent years, researchers have become more interested in these methods because they have been shown to be very effective

at removing pollutants, especially dyes, from water. The removal of cationic dye Rhodamine B (RhB) through the adsorption process using alumina NPs, which were synthesized via solvothermal method and modified with anionic surfactant SDS, has also been investigated. After four regeneration cycles, the modified NPs maintained a RhB removal

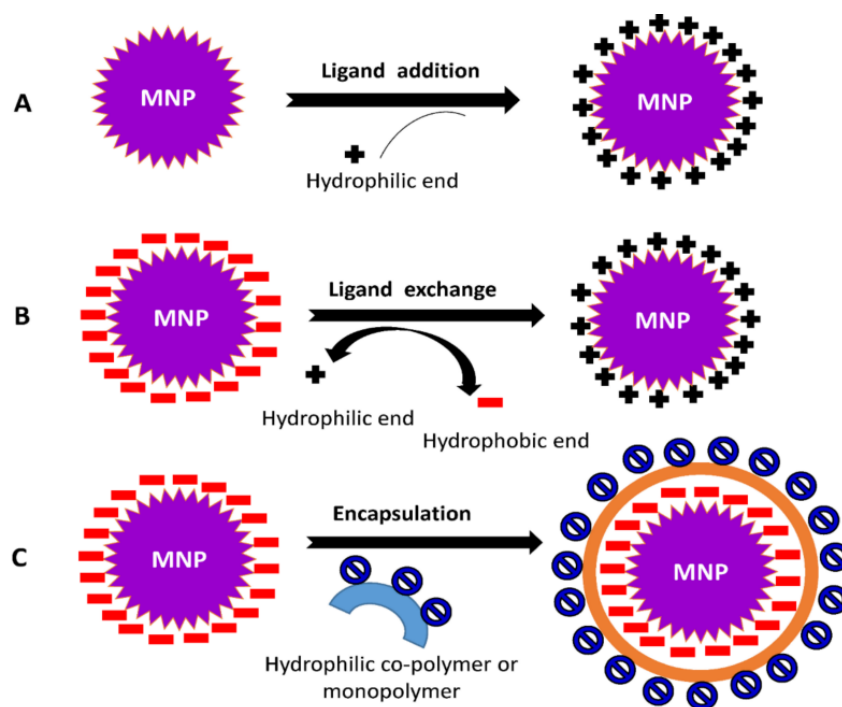


Fig. 3. Common mechanisms involved in surface modification of NPs (A) ligand addition, (B) ligand exchange, and (C) encapsulation [40]

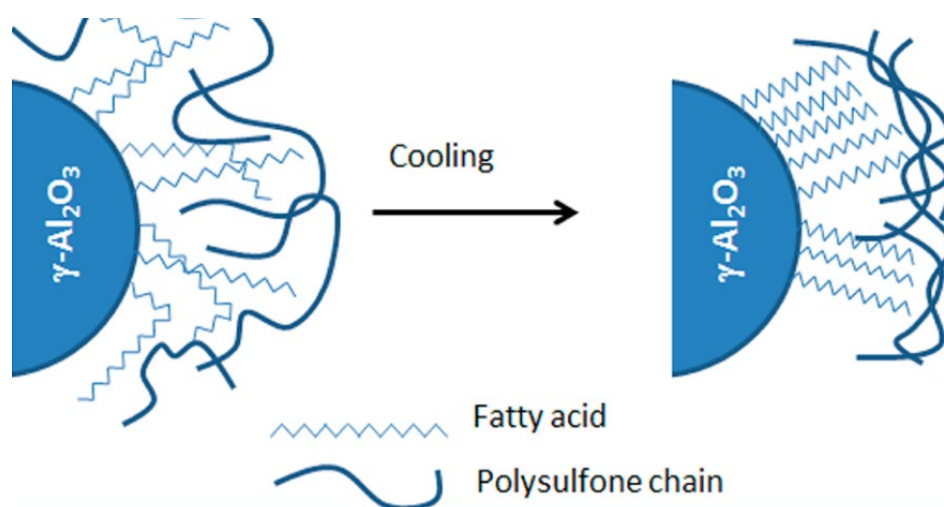


Fig. 4. Surface modification of alumina particles with fatty acids for dispersion in a polysulfone matrix. Reproduced with permission from Ref. [55]

efficiency exceeding 86% and achieved a high adsorption capacity of 165 mg/g [45].

The surface modification of both major nano-alumina phases, namely alpha- and gamma-alumina, has demonstrated promising results. The surface modification with SDS led to a substantial enhancement in the adsorption capacity in comparison with unmodified α - Al_2O_3 . The modified α - Al_2O_3 demonstrated remarkable reusability, maintaining over 98% removal efficiency after four regeneration cycles and achieving near-complete removal of RhB in actual textile wastewater samples [46]. A series of investigations focused on the removal of several basic synthetic dyes used in the textile industry including BB1, BR46, BY28, BB41, BY40 and BR18 with particular emphasis on addressing environmental concerns were carried out. Under optimized conditions, the SDS modified γ -alumina NPs achieved dye removal efficiencies exceeding 94%. Validation experiments confirmed the superior performance of the modified NPs, with adsorption efficiencies exceeding 90%, significantly outperforming unmodified NPs, which showed efficiencies below 60% [47-49].

A study has highlighted the advantages of surface modification and functionalization of nano-alumina. In this work, a novel adsorbent, 2,4-dinitrophenyl hydrazine-functionalized γ -alumina NPs (DNPH- γ -alumina) coated with SDS, was synthesized and evaluated for its efficiency in removing both anionic (AYR) and cationic (MB)

dyes from aqueous solutions. The high uptake and selectivity for DNPH demonstrate that surface functionalization significantly enhances the performance of γ -alumina, suggesting its broader applicability for the removal of diverse pollutants, including dyes and metal ions [50]. Conventional γ - Al_2O_3 has been shown to have limitations in wastewater treatment, including pH-dependent removal efficiency and low adsorption capacity for cationic dyes. In order to address these challenges, a pH-independent nano-sized γ -alumina was synthesized via dealumination of kaolin using nitric acid, followed by ammonia-induced precipitation in the presence of mixed surfactants. The incorporation of cetyltrimethylammonium bromide (CTAB) and Triton X-100 (TX100) surfactants promoted enhanced particle interactions and inhibited aggregation, resulting in increased surface area and improved adsorption performance. The synthesized alumina powders exhibited consistent dye removal efficacy across a broad pH range and demonstrated significantly higher adsorption capacity. This material has been identified as an efficient adsorbent for cationic dye removal from aqueous solutions [51]. Surfactants, in addition to modifying the nano-alumina surface, can be used in the synthesis procedure to produce highly effective NPs. A facile synthesis route has been developed for producing γ -alumina NPs using formamide as a precipitating agent and the non-ionic surfactant Tween-80 as a soft templating agent. The resulting NPs exhibited

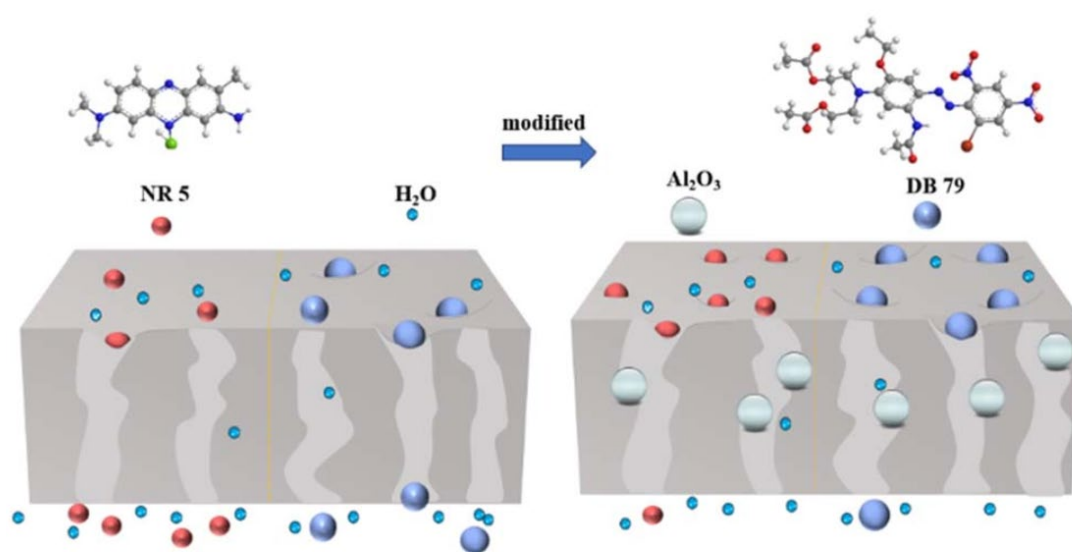


Fig. 5. Schematic of membrane filtration of dyes [74]

high surface area and demonstrated excellent adsorption capacity for the cationic dye MB [52]. Poly(vinylbenzyltrimethylammonium chloride) (PVBTAAC)-modified α - Al_2O_3 NPs have been developed as a novel adsorbent for the removal of the azo dye New Coccine (NCC) from aqueous solutions [53]. It was also applied as an effective agent for the adsorptive removal of the azo dye acid orange G (AOG). This nano adsorbent exhibited effective dye removal performance along with high reusability, indicating their potential for repeated use in wastewater treatment applications [54].

Increased adsorption capacity, selective dye removal, broader pollutant range, enhanced surface properties, pH-independent performance, reusability and durability, practical applicability, multi-functional capabilities are capabilities have been demonstrated in studies on nano-alumina after modification or functionalization. Consequently, surface-modified and functionalized nano-alumina exhibits superior performance in the removal of dyes from water when compared to unmodified nano-alumina. The material's versatility, high efficiency, and reusability make it a promising adsorbent for advanced wastewater treatment and pollutant remediation.

3.3. Alumina-based nanocomposites

Nanocomposites are multi-phase materials with at least one nanoscale component dispersed within a matrix (Fig. 4) [55]. This creates a three-dimensional structure that gives it properties that are different from regular materials.

Nanocomposite-based adsorbents offer distinct advantages for wastewater treatment by combining high surface area and tuned porosity with synergistic binding mechanisms across multiple phases. [56].

Alumina-based nanocomposites have attracted a lot of attention because of their great surface characteristics, mechanical stability, and resistance to thermal degradation [57]. These sorbents have also demonstrated efficacy in the removal of dyes from wastewater. An Al_2O_3 /graphene oxide/halloysite nanotube (Al_2O_3 /GO/HNT) nanocomposite was synthesized and characterized to evaluate its adsorption efficiency toward both cationic MB and anionic CR dyes in wastewater. Thermodynamic analysis indicated a spontaneous and exothermic adsorption process. Moreover, the composite effectively removed Cu (II), oxytetracycline, and 2-chlorophenol,

demonstrating its potential as a versatile adsorbent for dyes, heavy metals, and organic contaminants [58].

Mixed iron/aluminum oxide (Fe_2O_3 - Al_2O_3) nanocomposites were synthesized via a hydrothermal method and functionalized with the cationic surfactant CTAB to enhance their adsorption capacity for the anionic dye Acid Orange 67 (AO67) from aqueous solutions. Under optimized conditions, the CTAB-modified nanocomposites exhibited high removal efficiency for AO67 and other dyes, including RB222, RY145, and AR37, from simulated wastewater. These results suggest that the modified Fe_2O_3 - Al_2O_3 nanocomposite has promise as an effective adsorbent for treating dye-contaminated effluents in water purification applications [59]. An alumina-zirconia (Al_2O_3 - ZrO_2) composite was synthesized via the combustion method and evaluated as an adsorbent for the removal of CR and MB dyes from aqueous solutions. The adsorption performance was found to be more strongly influenced by the density and accessibility of active sites than by the specific surface area alone. These findings underscore the potential of Al_2O_3 - ZrO_2 composites as efficient and cost-effective adsorbents for the treatment of dye-contaminated wastewater [60]. Another composite adsorbent comprising chitosan, mesoporous silica (MCM-41), and nano-sized gamma-alumina (CS/MCM-41/Nano- Al_2O_3) was successfully synthesized. The resulting γ -alumina NPs exhibited high adsorption capacity for the cationic dye MB, highlighting their potential in dye removal applications [61].

Despite the investigation of numerous polymeric composite adsorbents for dye removal in wastewater treatment, further research is necessary to enhance their adsorption efficiency and commercial applicability, particularly in conjunction with carbonization and activation techniques. It is noteworthy that the application of alumina-polymeric composites for the removal of commercial dyes such as CR dye and Safranin O (SF) has not been thoroughly explored. In order to address this gap, a nano-alumina-doped catechol formaldehyde resin composite was synthesized via suspension polymerization that exhibited a higher adsorption capacity for the anionic dye CR compared to the cationic dye SF, suggesting its potential application as an effective adsorbent for the removal of anionic pollutants from aqueous environments [62]. In line with advancements in

alumina-based nanocomposites, synthesis of a novel hybrid adsorbent, gamma-alumina dawsonite has been reported which has been functionalized with bio-based substances. This novel adsorbent has been termed B-BBS0.4. The adsorption performance of the material was evaluated using cationic dye Crystal Violet (CV) and emerging contaminants Atenolol and carbamazepine as model substances. The synthesized composite exhibited a high adsorption capacity and rapid kinetics, with a reaction time of less than 30 minutes [63]. A recent study examined the adsorption of CR dye from aqueous solutions using ZnO and Al₂O₃/ZnO composite adsorbents. ZnO NPs were synthesized via a co-precipitation method, while Al₂O₃ for the composite was sourced from recycled aluminum waste. Adsorption occurred rapidly within the first 15 minutes and reached equilibrium by 45 minutes. Thermodynamic analysis revealed the adsorption process to be spontaneous and endothermic, with the Al₂O₃/ZnO composite demonstrating greater spontaneity than ZnO alone. These findings indicate that the incorporation of Al₂O₃ enhances the adsorption efficiency of ZnO for CR dye removal [64]. Recently, a novel composite adsorbent composed of alumina derived from alum physically mixed with acid-activated clay (Alumina/H⁺-Clay) was synthesized via a straightforward physical blending method. The composite's efficacy for the removal of MG dye was systematically evaluated and confirmed, demonstrating enhanced adsorption performance [65].

From the standpoint of environmental and natural resources engineering, the development of sustainable and efficient remediation technologies remains a critical priority. Commersonia bartramia leaf extract has been utilized for the first time as a green reducing agent in the synthesis of copper NPs, following an environmentally benign approach. The synthesis incorporated nano-alumina as a non-toxic support material to form Cu/Al₂O₃ nanocomposites. The catalytic efficiency of the Cu/Al₂O₃ nanocomposites was assessed through the reduction of aqueous pollutants, specifically DNPH, CR and MB dyes, under ambient conditions. The nanocomposites exhibited high catalytic performance and demonstrated excellent reusability across multiple reaction cycles with minimal activity loss, underscoring their potential as green and sustainable catalysts for environmental remediation and wastewater treatment applications [66].

The studied fabricated alumina-based nanocomposites exhibit superior physical and chemical properties, enhanced adsorption efficiency, versatility in dye and pollutant removal, improved kinetics and rapid adsorption, sustainability and environmental compatibility, high reusability, and cost-effectiveness for removing a broad spectrum of synthetic dyes and pollutants from wastewater.

3.4. Nano-alumina based membranes and innovative adsorbents

This subsection encompasses studies with distinctive innovations that do not fall under the previously discussed categories. A novel approach was developed for the simultaneous extraction and preconcentration of MG and basic fuchsin (FU) dyes from aqueous media using a molecularly imprinted polymer-coated nano-alumina adsorbent (MIP@Nano-Al₂O₃). The adsorbent was synthesized via a surface molecular imprinting technique and characterized using a variety of related techniques. The method relies on the selective adsorption of MG and FU and its applicability was confirmed through successful analysis of seafood and environmental water samples [67]. A flexible, self-supporting membrane consisting of ultrafine alumina-silica NFs was successfully fabricated using the electrospinning technique and employed as an adsorbent for the removal of RR-120 dye from aqueous solutions. Following adsorption, the nanofiber membrane could be easily separated and reused, exhibiting outstanding flexibility, recoverability, and reusability [68]. A novel mesoporous silica-alumina oxide (comprising 97% SiO₂ and 3% Al₂O₃), synthesized via the pyrogenic method, was employed as an adsorbent for the removal of selected dyes - C.I. Acid Orange 7 (AO7, acid dye), C.I. Reactive Black 5 (RB5, reactive dye), and C.I. Direct Blue 71 (DB71, direct dye) - as well as heavy metal ions (Co²⁺, Cu²⁺, Ni²⁺, Zn²⁺) from aqueous solutions and wastewater. The results demonstrated the high efficacy of this mixed oxide material as an adsorbent for the removal of diverse pollutants from contaminated water sources [69]. Magnetic nano-alumina, serving as a readily separable adsorbent, has been utilized for the removal of the toxic azo dye CR from aqueous solutions. The adsorbent exhibited a favorable adsorption capacity for the targeted dye, indicating its potential for effective dye remediation [70]. A novel adsorbent,

humic acid-functionalized alumina (HAFA) NPs, was synthesized via a precipitation method and evaluated for its effectiveness in the removal of MB dye from aqueous solutions. The findings suggested that the adsorption process was effective. Notably, reusability tests demonstrated that the HAFA NPs exhibited high adsorption efficiency over five consecutive cycles, indicating their potential for repeated use in dye removal applications [71].

Ceramic membranes currently occupy a small portion of the filtration membrane market due to high production costs and complex fabrication processes. To address this, a study introduced a rapid, one-step molding method for fabricating alumina ultrafiltration membranes using a camphene-based freeze-casting technique combined with surface airflow treatment. This method allows for the simultaneous formation of a thin separation layer and a macroporous support, simplifying production. The resulting membranes exhibited excellent performance, achieving 99.6% rejection of Direct Red 80 dye, highlighting their potential for cost-effective and scalable industrial ultrafiltration applications [72]. Nano-alumina has shown versatility in removing diverse pollutants. A breakthrough approach involved designing phenanthridine-based salicylaldehyde ligands for pollutant/metal ion detection, which were then engineered into novel mononuclear Al(III) complexes. These were transformed via sol-gel methods into ultra-small (3 nm) α -alumina NPs. Remarkably, these NPs achieved >93% solar-light-driven photodegradation of RhB and Methyl Orange in 140 minutes, surpassing prior benchmarks, demonstrating their exceptional potential as rapid, solar-responsive photocatalytic remediators [73]. To enhance the resistance of ultrafiltration membranes against dye fouling to ensure the efficient treatment of dye wastewater, polyvinylidene fluoride membranes were modified with aluminum oxide (Al_2O_3), which was introduced in two forms: as a sol and as a nanopowder. Membranes incorporating 20% Al_2O_3 sol exhibited superior performance compared to those modified with 1.0 wt% Al_2O_3 nanopowder, demonstrating improved pore structure, mechanical strength, and elevated water flux. These modifications resulted in a substantial enhancement of membrane hydrophilicity, dye rejection efficiency, and antifouling capability. The membranes demonstrated dye retention rates that exceeded 96% for neutral red 5 and dispersed navy

blue 79 (Fig. 5), while exhibiting high recovery rates of over 92% across three filtration cycles. These findings underscore the effectiveness and operational durability of the membranes in treating complex dye-laden wastewaters [74].

The study of reviewed works shows that innovative nano-alumina based nanoadsorbents have many advantages, including being selective, efficient, reusable, and able to be recovered and used many times. They are also versatile, efficient, reusable, and scalable. These nanoadsorbents offer a solution for removing a wide range of pollutants, especially synthetic dyes, from wastewater and makes them good choices for industrial and environmental water treatment.

4. Conclusion

Water pollution caused by synthetic dyes is a serious global problem that affects both the environment and human health. Alumina-based NMs have shown excellent dye-removal performance because of their large surface area, adjustable pore structure, and good chemical stability. Advances in synthesis methods such as hydrothermal, sol-gel, combustion, and green waste-derived processes have improved their crystallinity and adsorption capacity. Both γ - and α -alumina phases exhibit strong dye adsorption and photocatalytic activity, depending on their structural properties. Surface modification and functionalization also play key roles in enhancing the performance of nano-alumina. Approaches using surfactants (such as SDS) or chemical functional groups help improve particle dispersion, selectivity, and adsorption efficiency, often achieving more than 90% dye removal. Alumina-based nanocomposites show fast adsorption, good reusability, and the ability to remove both anionic and cationic dyes. Green synthesis using plant extracts or recycled aluminum sources increases sustainability and cost-effectiveness. Hybrid materials such as molecularly imprinted polymers, electrospun nanofibers, mesoporous silica alumina oxides, and modified membranes further enhance adsorption performance, mechanical strength, hydrophilicity, and antifouling properties, often achieving dye rejection above 96%. Overall, alumina-based NMs are efficient, sustainable, and scalable materials for wastewater treatment. Future work should focus on improving synthesis routes for large-scale production, enhancing long-term stability, and developing hybrid composites with

carbonaceous or polymeric materials to improve performance in complex and real wastewater systems.

Abbreviations

NMs: nanomaterials
NPs: nanoparticles
AR18: Acid Red 18
RR120: Reactive Red 120
AR14: Acid Red 14
CR: Congo Red
OG: Orange G
AOG: acid orange G
NCC: New Coccine
PVBTA: Poly(vinylbenzyltrimethylammonium chloride)
MB: Methylene Blue
RG19: Reactive Green 19
RY160: Reactive Yellow 160
RR-141: Reactive Red 141
EBT: Eriochrome Black T
BB9: Basic Blue 9
BB1: Basic Brown 1
BR46: Basic Red 46
BY28: Basic Yellow 28
BB41: Basic Blue 41
BY40: Basic Yellow 40
BR18: Basic Red 18
SDS: Sodium dodecyl sulfate
MG: malachite green
RhB: Rhodamine B
FU: fuchsine
SF: Safranin O
C.I.: Colour Index
AO7: Acid Orange 7
RB5: Reactive Black 5
DB71: Direct Blue 71
AYR: Alizarin Yellow R
DNPH: 2,4-dinitrophenyl hydrazine
CTAB: cetyltrimethylammonium bromide
TX100: Triton X-100
AO67: Acid Orange 67
HAF: humic acid-functionalized alumina
GO/HNT: graphene oxide/halloysite nanotube

Declarations

Ethical approval and consent to participate

Not applicable

Consent for publication

The study does not involve any human participants, human data, or human tissues.

Availability of data and material

The images and datasets supporting the findings of this review are available openly within the referenced articles.

Competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- [1] M. Bhadarka, D. Vaghela, B. Kamleshbhai, H. Sikotariya, N. Kharadi, M. Bamaniya, K. Makwana, P. Verma, *Water Pollution: Impacts on Environment*, 2024, pp. 163–181.
- [2] T. Islam, M.R. Repon, T. Islam, Z. Sarwar, M.M. Rahman, Impact of textile dyes on health and ecosystem: a review of structure, causes, and potential solutions, *Environ Sci Pollut Res Int* 30 (2023) 9207–9242. <https://doi.org/10.1007/s11356-022-24398-3>
- [3] T. Akter, A.T. Protity, M. Shaha, M. Al Mamun, A. Hashem, The Impact of Textile Dyes on the Environment, in: A. Ahmad, M. Jawaid, M.N. Mohamad Ibrahim, A.A. Yaqoob, M.B. Alshammari (Eds.) *Nanohybrid Materials for Treatment of Textiles Dyes*, Springer Nature Singapore, Singapore, 2023, pp. 401–431.
- [4] H. Moghanian, M. Bagtash, M. Naseh, Removal of some potentially toxic metal ions and dyes from aqueous solutions by nanobiosorbent: A review, *Colloid & Nanoscience Journal* 3 (2025) 478–500. <https://doi.org/10.61186/CNJ.3.1.478>
- [5] A.P. Periyasamy, Recent Advances in the Remediation of Textile-Dye-Containing Wastewater: Prioritizing Human Health and Sustainable Wastewater Treatment, *Sustainability* 2024. <https://doi.org/10.3390/su16020495>
- [6] T.A. Saleh, Nanomaterials: Classification, properties, and environmental toxicities, *Environ Technol Innovation* 20 (2020) 101067. <https://doi.org/10.1016/j.eti.2020.101067>
- [7] M. Salavati-Niasari, R. Monsef, A. Karami, A.M. Aljeboree, F.H. Alsultany, H.H. Hamza, Sonochemical preparation and characterization of ErVO₄/g-C₃N₄ nano-photocatalysts for removal of water-soluble organic dyes under visible light exposures, *Results Eng* 28 (2025) 107764. <https://doi.org/10.1016/j.rineng.2025.107764>
- [8] A. Panahi, R. Monsef, E.A. Dawi, A.S. Hussein, M. Salavati-Niasari, Green auto-combustion synthesis and characterization of TmVO₄ nanostructures in the presence carbohydrate sugars and their application as Visible-light photocatalyst, *Sol. Energy* 258 (2023) 372–382. <https://doi.org/10.1016/j.solener.2023.04.030>
- [9] S. Zinatloo-Ajabshir, M. Baladi, O. Amiri, M. Salavati-Niasari, Sonochemical synthesis and characterization of silver tungstate nanostructures as visible-light-driven photocatalyst for waste-water treatment, *Sep Purif Technol* 248 (2020) 117062. <https://doi.org/10.1016/j.seppur.2020.117062>

- [10] R. Mahesh, K. Vora, M. Hanumanthaiah, A. Shroff, P. Kulkarni, S. Makuteswaran, S. Ramdas, H.L. Ramachandrai, A.V. Raghu, Removal of pollutants from wastewater using alumina based nanomaterials: A review, *Korean J chem eng* 40 (2023) 2035–2045. <https://doi.org/10.1007/s11814-023-1419-x>
- [11] T. Ilame, A. Ghosh, The promising applications of nanoparticles for synthetic dyes removal from wastewater: recent review, *Manag Environ Qual* 33 (2022) 451–477. <https://doi.org/10.1108/MEQ-07-2021-0179>
- [12] C. Kathing, G. Saini, A Review of Various Treatment Methods for the Removal of Dyes from Textile Effluent, *Recent Progress in Materials* 04 (2022) 028. <https://doi.org/10.21926/rpm.2204028>
- [13] K.A.A. Terrazas, M.C. Nahúm, Á.J.R. Baltazar, O.T. Pérez, S.Y.R. López, REVIEW OF ALUMINA IN ADSORPTION PROCESSES FOR EMERGING POLLUTANTS, *Int J Res Granthaalayah* 9 (2011) 435–453. <https://doi.org/10.21921/granthaalayah.v9.i4.2021.3846>
- [14] B. Mekuye, B. Abera, Nanomaterials: An overview of synthesis, classification, characterization, and applications, *Nano Select* 4 (2023) 486–501. <https://doi.org/10.1002/nano.202300038>
- [15] A. Shoukat, M. Rafique, A. Ayub, B. Razzaq, M. Bilal Tahir, M. Sagir, An Insight into Properties and Characterization of Nanostructures, in: M.B. Tahir, M. Rafique, M. Sagir (Eds.) *Nanotechnology: Trends and Future Applications*, Springer Singapore, Singapore, 2021, pp. 39–81.
- [16] M. Mahinroosta, R.M. Moattari, Chapter 10 - Alumina-based nanoadsorbents for wastewater treatment, in: C. Verma, J. Aslam, M.E. Khan (Eds.) *Adsorption through Advanced Nanoscale Materials*, Elsevier, 2023, pp. 205–239.
- [17] K. Ravindhranath, M. Ramamoorthy, Nano aluminum oxides as adsorbents in water remediation methods: A review, *Rasayan J Chem* 10 (2017) 716–722. <https://doi.org/10.7324/RJC.2017.1031762>
- [18] H. Zhu, K. Liu, Z. Meng, H. Wang, Y. Li, Properties and Preparation of Alumina Nanomaterials and Their Application in Catalysis, *Micro* 5 (2025) 38. <https://doi.org/10.3390/micro5030038>
- [19] R. Jain, S. Pooja, S. Shalini, M. Jyoti, D. and Pathak, Adsorption kinetics and thermodynamics of hazardous dye Tropaeoline 000 onto Aeroxide Alu C (Nano alumina): a non-carbon adsorbent, *Desalin Water Treat* 52 (2014) 7776–7783. <https://doi.org/10.1080/19443994.2013.837009>
- [20] M.H. Dehghani, Z. Norozi, E. Nikfar, M. Vosoghi, Investigation of Removal Efficiency of Nano Sized Alumina for Removal of Acid Red 18 from Aqueous Solutions, *Alborz-Health*, 3 (2014) 171. <https://doi.org/10.18869/acadpub.aums.3.3.171>
- [21] K. Nadafi, M. Vosoughi, A. Asadi, M.O. Borna, M. Shirmardi, Reactive Red 120 dye removal from aqueous solution by adsorption on nano-alumina, *J Water Chem Technol* 36 (2014) 125–133. <https://doi.org/10.3103/S1063455X14030059>
- [22] S. Singh, V.C. Srivastava, T.K. Mandal, I.D. Mall, Synthesis of different crystallographic Al₂O₃ nanomaterials from solid waste for application in dye degradation, *RSC Adv* 4 (2014) 50801–50810. <https://doi.org/10.1039/C4RA08842E>
- [23] A. Neisi, M. Vosoughi, A. Asadi, M.J. Mohammadi, M. Shirmardi, M. Fazlzadeh, A. Zahedi, Removal of Acid Red 14 by Nano-Alumina and Micro-Alumina Powder From Aqueous Solution, *J Sabzevar Univ Med Sci* 23 (2016) 478–489.
- [24] U.N. Afangide, A.O. Odiongenyi, Adsorption and Thermodynamic Studies on the Removal of Congo Red Dye from Aqueous Solution by Alumina and Nano-alumina. *Commun Phys Sci* 4 (2019) 1–7.
- [25] S. Banerjee, S. Dubey, R.K. Gautam, M.C. Chattopadhyaya, Y.C. Sharma, Adsorption characteristics of alumina nanoparticles for the removal of hazardous dye, Orange G from aqueous solutions, *Arabian J Chem* 12 (2019) 5339–5354. <https://doi.org/10.1016/j.arabjc.2016.12.016>
- [26] Z. Bonyadi, Z. Fouladi, A. Robatjazi, M. Zahmatkesh Anbarani, Reactive red-141 removal from synthetic solutions by γ -Al₂O₃ nanoparticles: process modeling, kinetic, and isotherm studies, *Appl Water Sci* 13 (2022) 52. <https://doi.org/10.1007/s13201-022-01854-6>
- [27] H. Zhang, Y. Ruan, Y. Feng, M. Su, Z. Diao, D. Chen, L.a. Hou, P.-H. Lee, K. Shih, L. Kong, Solvent-free hydrothermal synthesis of gamma-aluminum oxide nanoparticles with selective adsorption of Congo red, *J Colloid Interface Sci* 536 (2019) 180–188. <https://doi.org/10.1016/j.jcis.2018.10.054>
- [28] M. Subramanian, M. Pathak, Crystal structure, Hirshfeld surface analysis and DFT investigation of new aluminium(III) derivative: A prominent precursor of nano alumina for dye degradation and sensor material, *Polyhedron* 246 (2023) 116696. <https://doi.org/10.1016/j.poly.2023.116696>
- [29] N. Mnasri, W. Sassi, R. Msaadi, M. Serdechnova, C. Blawert, S. Ammar, Emergent α - corundum nano-Al₂O₃ material for Eriochrome Black T removal, *Emergent Mater* 7 (2024) 973–986. <https://doi.org/10.1007/s42247-023-00623-8>
- [30] R. Goswami, Y. Goswami, M. Shahrestasni, Synthesis And Characterization of Aluminium Oxide Nano Adsorbents Via a Sustainable Combustion Method for Methyl Red Remediation, *Rev Roum Chim* 69 (2024) 595–603. <https://doi.org/10.33224/rrch.2024.69.10-12.09>
- [31] N.A. Ghulam, A.M. Nsaif, D.E. and Sachit, Preparation of synthetic alumina from aluminium foil waste and investigation of its performance in the removal of RG-19 dye from its aqueous solution, *Indian Chem Eng* 62 (2020) 301–313. <https://doi.org/10.1080/00194506.2019.1677512>
- [32] F.I.M.S. Sangor, M.A. Al-Ghouthi, Waste-to-value: Synthesis of nano-aluminum oxide (nano- γ -Al₂O₃) from waste aluminum foils for efficient adsorption of methylene blue dye, *Case Stud Chem Environ Eng* 8 (2023) 100394. <https://doi.org/10.1016/j.csee.2023.100394>
- [33] H.H.A. Ghafar, E. Radwan, N. Khalil, Y. Eljamal, Removal of reactive yellow 160 from aqueous solution by alumina nanoparticles derived from aluminium waste residue, *Egypt J Chem* 63 (2020) 2887–2899. <https://doi.org/10.21608/ejchem.2020.21532.2291>
- [34] F. Salah Aljohani, M. El-Khatib, Impact of different phase structure nano Al₂O₃ arc discharge prepared on MB dye removal, *J Cryst Growth* 643 (2024) 127811. <https://doi.org/10.1016/j.jcrysgro.2024.127811>
- [35] G. Tchanang, J.M. Kepdieu, C.N. Djangang, C.J. Ekani, M.Y. Baldé, C.F. Abi, P. Blanchart, Application of γ -Nanoalumina-based Kaolinitic Clay (Na-Kc) in the Adsorptive Removal of Basic Blue 9 from aqueous synthetic Solution, 02 (2024) January. <https://doi.org/10.21203/rs.3.rs-3827286/v1>
- [36] A.H. Gharbi, S.E. Laouini, H. Hemmami, A. Bouafia, M.T. Gherbi, I. Ben Amor, G.G. Hasan, M.M.S. Abdullah, T. Trzpieciński, J.A. Abdullah, Eco-Friendly Synthesis of Al₂O₃ Nanoparticles: Comprehensive Characterization Properties, Mechanics, and Photocatalytic Dye Adsorption Study, *Coatings* 14 (2024). <https://doi.org/10.3390/coatings14070848>
- [37] S. Ranjbar, G. Haghdoost, A. Ebadi, Adsorption of Two Textile Dyes from Aqueous Solution by Synthetic Gamma

- Alumina Particles: Isotherm, Kinetic and Thermodynamic, *Chem Method* 5 (2021) 70–81. <https://doi.org/10.22034/chemm.2021.119183>
- [38] S. Mobasser, M. Taha, A.A. Firoozi, H. Fakour, Engineered Nano Alumina as a Novel and Promising Adsorbent for Removal of DDT from Soil. (Case Study: Malaysian Residual Soil), 8 (2022) 34–53.
- [39] E.N. Ngouangna, M. Zaidi Jaafar, M. Norddin, A. Agi, J.O. Oseh, S. Mamah, Surface modification of nanoparticles to improve oil recovery Mechanisms: A critical review of the methods, influencing Parameters, advances and prospects, *J Mol Liq* 360 (2022) 119502. <https://doi.org/10.1016/j.molliq.2022.119502>
- [40] F. Ahmad, M.M. Salem-Bekhit, F. Khan, S. Alshehri, A. Khan, M.M. Ghoneim, H.-F. Wu, E.I. Taha, I. Elbagory, Unique Properties of Surface-Functionalized Nanoparticles for Bio-Application: Functionalization Mechanisms and Importance in Application, *Nanomaterials* 2022. <https://doi.org/10.3390/nano12081333>
- [41] T. Bayram, S. Bucak, D. Ozturk, BR13 dye removal using sodium dodecyl sulfate modified montmorillonite: Equilibrium, thermodynamic, kinetic and reusability studies, *Chem Eng Process Process Intensif* 158 (2020) 108186. <https://doi.org/10.1016/j.cep.2020.108186>
- [42] V.D. Nguyen, A.-T. Vu, T.V. La, Fabrication of high-purity alumina particles by spray drying and surface modification with SDS for methylene blue removal, *Particuology* 102 (2025) 27–40. <https://doi.org/10.1016/j.partic.2025.03.019>
- [43] E. Mohammadifar, F. Shemirani, B. Majidi, M. Ezoddin, Application of modified nano- γ -alumina as an efficient adsorbent for removing malachite green (MG) from aqueous solution, *Desalin Water Treat* 54 (2015) 758–768. <https://doi.org/10.1080/19443994.2014.890549>
- [44] J. Zolgharnein, M. Bagtash, T. Shariatmanesh, Simultaneous removal of binary mixture of Brilliant Green and Crystal Violet using derivative spectrophotometric determination, multivariate optimization and adsorption characterization of dyes on surfactant modified nano- γ -alumina, *Spectrochim Acta Part A* 137 (2015) 1016–1028. <https://doi.org/10.1016/j.saa.2014.08.115>
- [45] T.P. Chu, N.T. Nguyen, T.L. Vu, T.H. Dao, L.C. Dinh, H.L. Nguyen, T.H. Hoang, T.S. Le, T.D. Pham, Synthesis, Characterization, and Modification of Alumina Nanoparticles for Cationic Dye Removal, *Materials* 2019. <https://doi.org/10.3390/ma12030450>
- [46] T.H. Yen Doan, T.P. Minh Chu, T.D. Dinh, T.H. Nguyen, T.C. Tu Vo, N.M. Nguyen, B.H. Nguyen, T.A. Nguyen, T.D. Pham, Adsorptive Removal of Rhodamine B Using Novel Adsorbent-Based Surfactant-Modified Alpha Alumina Nanoparticles, *J Anal Methods Chem* 2020 (2020) 6676320. <https://doi.org/10.1155/2020/6676320>
- [47] M. Saadati, M. Iranifam, S.I. Mosavi, Removal of some textile cationic dyes from industrial wastewater using modified gamma alumina nanoparticles, *JACR* 17 (2024) 60–75. Retrieved from <https://sanad.iau.ir/en/Article/1044851>
- [48] M. Saadati, S. Sadigzadeh, M. Iranifam, Surfactant modified γ -alumina nanoparticles for removal of cationic dyes from wastewater, *J Indian Chem Soc* 102 (2025) 102023. <https://doi.org/10.1016/j.jics.2025.102023>
- [49] M. Saadati, S. Sadigzadeh, Surface-Modified γ -Alumina Nanoparticles for Efficient Adsorption of some Cationic Dyes from Wastewater, *Colloid & Nanoscience Journal*, 3 (2025) 533–546. <https://doi.org/10.61882/CNJ.3.1.533>
- [50] W.T. Al-Rubayee, O.F. Abdul-Rasheed, N.M. Ali, Preparation of a Modified Nanoalumina Sorbent for the Removal of Alizarin Yellow R and Methylene Blue Dyes from Aqueous Solutions, *J Chem* 2016 (2016) 4683859. <https://doi.org/10.1155/2016/4683859>
- [51] S. Ferdowsi, A. Salem, S. Salem, Spectrophotometrical analysis for fabrication of pH-independent nano-sized γ -alumina by dealumination of kaolin and precipitation in the presence of surfactant composites, *Spectrochim Acta Part A* 218 (2019) 109–118. <https://doi.org/10.1016/j.saa.2019.03.103>
- [52] S. Ali, Y. Abbas, Z. Zuhra, I.S. Butler, Synthesis of γ -alumina (Al₂O₃) nanoparticles and their potential for use as an adsorbent in the removal of methylene blue dye from industrial wastewater, *Nanoscale Adv* 1 (2019) 213–218. <https://doi.org/10.1039/C8NA00014J>
- [53] T.H.Y. Doan, H.A. Pham, N.H. Nguyen, T.D. Le, T.B. Nguyen, T.S. Le, Adsorptive Removal of Azo Dye New Coccine Using High-Performance Adsorbent-Based Polycation-Modified Nano-Alpha Alumina Particles, *J Anal Methods Chem* 2022 (2022) 9425334. <https://doi.org/10.1155/2022/9425334>
- [54] T.H. Yen Doan, L. Van Dang, T.T. Trang Truong, T.N. Vu, T.S. Le, T.M. Thu Nguyen, M.N. Nguyen, T.T. Pham, S.-i. Yusa, T.D. Pham, Removal of Acid Orange G Azo Dye by Polycation-Modified Alpha Alumina Nanoparticles, *Chem Asian J* 18 (2023) e202300404. <https://doi.org/10.1002/asia.202300404>
- [55] S. Anaya, B. Serrano, B. Herrero, A. Cervera, J. Baselga, γ -Alumina Modification with Long Chain Carboxylic Acid Surface Nanocrystals for Biocompatible Polysulfone Nanocomposites, *ACS Appl Mater Interfaces* 6 (2014) 14460–14468. <https://doi.org/10.1021/am503744z>
- [56] H. Ghasemzadeh, S. Shidrang, A. Keshtkar Vanashi, Nanocomposite magnetic hydrogel based on κ -carrageenan and acrylic acid for the removal of Cd(II), Co(II), Cu(II), and Ni(II); Efficient adsorption enhanced by activated carbon and magnetic nanoparticles, *Int J Biol Macromol* 292 (2025) 139164. <https://doi.org/10.1016/j.ijbiomac.2024.139164>
- [57] Z. karimi, A. Allahverdi, F. Oshani, Investigation on the Removal of Dyes from Wastewater Using Alumina Composite Nano Adsorbent, *JSCW* 10 (2020) 41–59. <https://dor.isc.ac/dor/20.1001.1.22517278.1399.10.2.4.7>
- [58] M.A. Barakat, R. Kumar, M. Balkhyour, M.A. Taleb, Novel Al₂O₃/GO/halloysite nanotube composite for sequestration of anionic and cationic dyes, *RSC Adv* 9 (2019) 13916–13926. <https://doi.org/10.1039/C9RA02246E>
- [59] N. Hilal, O. Mostafa, Removal of Pollutant Textile Dye from Aqueous Solution Using Mixed Nanocomposite of Iron /Alumina Oxide and It's Modified with Cationic Surfactants. *Al-Azhar Bull Sci* 29 (2018) Article 32.
- [60] A.O. Adesina, E.O. A., M.N.D. S., S.J. and Olusegun, Adsorption of Methylene blue and Congo red from aqueous solution using synthesized alumina–zirconia composite, *Environ Technol* 42 (2021) 1061–1070. <https://doi.org/10.1080/09593330.2019.1652696>
- [61] A. Teimouri, N. Ghased, S.G. Nasab, S. Habibollahi, Statistical design of experiment as a tool for optimization of methylene blue sorption on CS/MCM-41/nano- γ alumina as a novel and environmentally friendly adsorbent: isotherm and kinetic studies, *Desalin Water Treat* 139 (2019) 327–341. <https://doi.org/10.5004/dwt.2019.23258>
- [62] V. Karthik, P. Selvakumar, N. Sivarajasekar, P. Megavarshini, N. Brinda, J. Kiruthika, K. Balasubramani, T. Ahamad, M. Naushad, Comparative and Equilibrium Studies on Anionic and Cationic Dyes Removal by Nano-Alumina-Doped Catechol Formaldehyde Composite, *J Chem* 2020 (2020) 7617989. <https://doi.org/10.1155/2020/7617989>
- [63] R. Sadraei, Fast, green and easy adsorption of dye and

- emerging contaminants by functionalized γ -AACH, *J Environ Chem Eng* 8 (2020) 103616. <https://doi.org/10.1016/j.jece.2019.103616>
- [64] M.O. Bello, R.T. Oyewumi-Musa, N. Abdus-Salam, N.M.T. Gbenro, O.G. Egbeneye, Adsorption of Congo Red Dye from Aqueous Solution using ZnO and Al₂O₃/ZnO Composite: Isotherm, Kinetic and Thermodynamic Data. *J Appl Sci Environ Manag* 26 (2022) 439-447. <https://doi.org/10.4314/jasem.v26i3.10>
- [65] F.Z. Soufal, A. Zehhaf, B.A. Reguig, F. Chouli, Adsorption efficiency of malachite green dye (MG) using a novel composite adsorbent based on synthesized alumina/acid-activated clay, *Desalin Water Treat* 273 (2022) 236-245. <https://doi.org/10.5004/dwt.2022.28872>
- [66] M. Nasrollahzadeh, Z. Issaabadi, S.M. Sajadi, Green synthesis of Cu/Al₂O₃ nanoparticles as efficient and recyclable catalyst for reduction of 2,4-dinitrophenylhydrazine, Methylene blue and Congo red, *Composites Part B* 166 (2019) 112-119. <https://doi.org/10.1016/j.compositesb.2018.11.113>
- [67] R. Mirzajani, M. and Bagheban, Simultaneous preconcentration and determination of malachite green and fuchsine dyes in seafood and environmental water samples using nano-alumina-based molecular imprinted polymer solid-phase extraction, *Int J Environ Anal Chem* 96 (2016) 576-594. <https://doi.org/10.1080/03067319.2016.1172215>
- [68] M.Z. Bin Mukhlis, Y. Horie, T. Nomiya, Flexible Alumina-Silica Nanofibrous Membrane and Its High Adaptability in Reactive Red-120 Dye Removal from Water, *Water Air Soil Pollut* 228 (2017) 371. <https://doi.org/10.1007/s11270-017-3546-7>
- [69] M. Wawrzkiwicz, M. Wiśniewska, A. Wołowicz, V.M. Gun'ko, V.I. Zarko, Mixed silica-alumina oxide as sorbent for dyes and metal ions removal from aqueous solutions and wastewaters, *Microporous Mesoporous Mater* 250 (2017) 128-147. <https://doi.org/10.1016/j.micromeso.2017.05.016>
- [70] S. Hassani, M. Shirani, A. Semnani, M. Hassani, A. Firooz, Removal of Congo red by magnetic nano-alumina using response surface methodology and artificial neural network, *Desalin Water Treat* 62 (2017) 241-251. <https://doi.org/10.5004/dwt.2017.0018>
- [71] S. Banerjee, Enhanced removal of methylene blue dye from its aqueous solutions using humic acid-functionalized alumina nanoparticles, *Res Chem Intermed* 44 (2018) 4119-4148. <https://doi.org/10.1007/s11164-018-3359-3>
- [72] Y. Liu, W. Zhu, K. Guan, C. Peng, J. Wu, Freezing-casting of alumina ultra-filtration membranes with good performance for anionic dye separation, *Ceram Int* 44 (2018) 11901-11904. <https://doi.org/10.1016/j.ceramint.2018.03.160>
- [73] S. Thanigachalam, P. Madhvesh, K.I. and Sathiyarayanan, Photodegradation of rhodamine-B and methyl orange employing nano-alumina developed from new aluminium(III) complex(es) associated with phenanthridine-salicylaldehyde derived ligands, *J Coord Chem* 75 (2022) 2189-2213. <https://doi.org/10.1080/00958972.2022.2120814>
- [74] R. Liu, J. Yang, R. Zhang, H. Li, R. Mu, Performance comparison of nano-Al₂O₃-modified PVDF membranes fabricated via two methods for enhanced dye removal, *RSC Adv* 15 (2025) 4163-4172. <https://doi.org/10.1039/D4RA08615E>