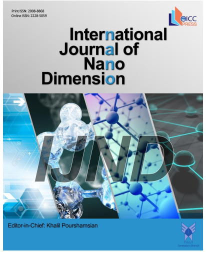


Volume 16, Issue 2, 162515 (1-11)

International Journal of Nano Dimension (IJND)

https://doi.org/10.57647/j.ijnd.2025.1602.15

Synthesis and characterization of aluminium oxide nanoparticles using ammonia precipitation method: a novel approach for environmentally friendly pollutant remediation in environmental system

Ranjana Goswami[1], Mahdi Shahrestani[1], Yogesh Chandra Goswami[1,*]

[1] *Nano Lab, School of Sciences, ITM University, Gwalior, MP, India.*

*Corresponding author: ycgoswami@gmail.com

Original Research

Received:
7 September 2024
Revised:
26 November 2024
Accepted:
29 November 2024

Abstract:

This study focuses on synthesizing aluminium oxide nanoparticles using aluminium chloride and investigates their potential for removing cadmium from wastewater. The synthesized nanoparticles were thoroughly characterized to determine their structural and luminescence properties. The results indicate that the nanoparticles possess a crystalline structure and exhibit luminescence behaviour in the visible region. X-ray diffraction analysis confirmed the formation of rhombohedral aluminium oxide nanoparticles. The XRD pattern revealed the (012), (104), (006), (202), (024), (116), and (300) peaks of Al_2O_3 nanoparticles with crystallite sizes ranging from 46-68 nm. Moreover, UV-Vis spectrophotometer analysis revealed a significant increase in absorption intensity when aluminium oxide nanoparticles were introduced, demonstrating their effectiveness as an adsorbent for cadmium removal from wastewater. Aluminium chloride yielded superior results in synthesizing aluminium oxide nanoparticles.

Keywords: Aluminium oxide; Coprecipitation; Metal oxide; Nanoparticles; Pollutant remediation

Introduction

Water is one of the prime and fundamental elements responsible for life on Earth. With two-thirds of the earth's surface covered by water and the human body consisting of 75 per cent water, it is evident that water is essential for human survival. Unfortunately, the quality of our drinking water has been severely compromised. It contains around 200 harmful commercial chemicals, bacteria, viruses, and inorganic minerals that make the water hard [1–4]. According to John Archer's around 60,000 tons of fifty different chemicals are debatably added to water each year, posing a significant threat to public health [5]. This situation highlights the urgent need for improved water treatment methods to ensure access to clean and safe drinking water for all. Water pollution is a significant threat to public health and the environment, with various harmful chemicals and pollutants contaminating our water sources. Some of the most abundant and dangerous pollutants found in water include chlorine, aluminium sulfate, and sodium fluoride [6]. For instance, tests carried out in Victoria in 1976 by the State Water Supply Commission indicated that fluoride is involved in the corrosion of copper pipes, leading to more poisonous leaching into the water. In addition to fluoride, water can be contaminated with lead, sodium silica fluoride slurry, sulfuric acid, sodium hypochlorite solution, calcium oxide, silt, rust, debris, larvae, asbestos, pesticides, herbicides, fertilizers from agricultural runoff, mould, fungi, industrial waste, toxic metals, amoebas, clay, and silica [7, 8]. The presence of these contaminants makes it increasingly challenging to access pure drinking water.

Among all these pollutants, heavy metals and metalloids are the most concerning, including chromium, mercury, lead, cadmium, and arsenic [9–12]. These toxic substances can accumulate in the human body and cause severe health problems, such as neurological disorders, cancer, and organ damage.

Effective water treatment and remediation methods are essential to minimise the risk of waterborne diseases and ensure access to clean and safe drinking water for all. Traditional water treatment methods, such as coagulation, flocculation, sedimentation, filtration, disinfection, sludge drying, fluoridation, and pH correction, have limitations in terms of effectiveness and cost. Studies conducted in the last decade suggest that advanced oxidation processes (AOPs), bio-remediation using microorganisms, and micro/nanobubbles have emerged as potential methods for water treatment [13–15]. AOPs involve the use of highly reactive hydroxyl radicals to oxidize organic pollutants in water, while bio-remediation exploits the ability of microorganisms to break down and remove pollutants [16]. Micro/nanobubbles, on the other hand, enhance the performance of traditional treatment methods such as flotation, sedimentation, and filtration, leading to higher removal efficiencies [17]. Adsorption using materials such as carbon nanotubes has also shown promise in removing heavy metals from wastewater [18]. Recent research has shown that these new methods have higher efficiencies and are more sustainable than traditional methods, making them promising alternatives for water treatment. These advances in water treatment methods have the potential to significantly improve the quality of drinking water, protecting public health and the environment.

Nanotechnology and nanomaterials have become increasingly important in environmental remediation due to their unique properties [19–21]. Their nanoscale size, large surface area, and noble properties such as chemical, optical, magnetic, and electrical properties make them ideal for the removal of pollutants from water. Several studies have reported the successful removal of various pollutants from water by nanomaterials [22–24]. For instance, metallic nanoparticles have been used to remove heavy metal ions from contaminated water. Wang *et al.* [25] demonstrated the removal of cadmium ions from water by graphene oxide-iron oxide hybrid nanocomposites. Similarly, iron oxide nanoparticles were used by Qu. et al. [26] to remove lead ions from water. Nanomaterials have also been used for the removal of organic pollutants from water [27–29]. Carbon-based nanomaterials, such as graphene oxide and carbon nanotubes, have been used to remove organic pollutants from water due to their high adsorption capacities [30, 31]. Silver nanoparticles are synthesised by various green routes and used for efficient water treatment [32–34].

Recently metal oxides and nanoparticles are proving crucial for environmental pollution remediation. For instance, iron lanthanum oxide nanoparticles exhibit enhanced photocatalytic degradation of organic pollutants [35]. Red phosphorus/ZnO nanohybrids are high-performance photocatalysts for pollutant degradation [36]. Mesoporous polyacrylamide/gelatin–iron lanthanum oxide nanohybrids effectively remove antibiotic drugs from wastewater [37]. Additionally, NiO–rGO nanohybrids efficiently degrade antibiotic pollutants under visible light [38, 39]. These advancements demonstrate the potential of nanomaterials in sustainable environmental clean-up. Additionally, metal-organic frameworks (MOFs) have been utilized for the removal of organic pollutants from water due to their large surface area, high porosity, and tunable properties [40]. SiO_2/ZIF-8 MOF nanocomposite and DNA/Carbon nanotubes are also reported for photocatalyst applications Furthermore, nanomaterials have been used for the removal of bacteria and viruses from water. Silver nanoparticles have been shown to have antimicrobial properties and can be used for the removal of bacteria from water [41].

Moreover, titanium dioxide nanoparticles have been used for the removal of viruses from water due to their photocatalytic properties [42]. The use of nanomaterials for water treatment is a promising field of research. Their unique properties make them effective for the removal of various pollutants from water. However, further research is needed to evaluate the potential risks associated with the use of nanomaterials in water treatment and to optimize their performance. MgO epoxy composites, MSNPS, hydroxyl apalite coating and bio surfaces also reported for various biomedical applications [43–47].

Nanomaterials can be synthesised through various chemical routes, each offering distinct advantages [48–51]. For instance, CuS nanorods can be synthesized by a co-precipitation route, where copper and sulphur precursors are mixed in solution, leading to the formation of randomly oriented self-assembled nanorods. CdS nanoparticles, known for their high luminescence, can be produced using microwave irradiation of a dithiocarbazate ligand as a single molecular precursor source. Alternatively, a sol-gel route can be employed to grow CdS nanostructures, providing controlled morphology and size, while a microwave-assisted ultrasonic sol-gel method can yield ultra-small CdS/CdSe core/shell nanostructures. These chemical synthesis methods highlight the versatility and efficiency of producing nanomaterials with tailored properties.

Aluminium oxide (Al_2O_3) is a widely used adsorbent for water purification due to its high surface area, thermal stability, and chemical inertness [52]. It has been reported that Al_2O_3-based adsorbents can effectively remove various contaminants such as heavy metals, dyes, and organic pollutants from wastewater [53–55]. Moreover, the use of Al_2O_3-based materials has shown promising results in removing emerging contaminants like pharmaceuticals and personal care products [56, 57]. The effectiveness of Al_2O_3-based adsorbents for water purification can be further enhanced by modifying their surface properties. For example, surface modification with functional groups like carboxyl, amino, and hydroxyl groups has improved the adsorption capacity of Al_2O_3-based materials [58, 59]. Additionally, incorporating other materials into Al_2O_3-based composites has been reported to enhance their adsorption performance. For example, incorporating magnetic nanoparticles into Al_2O_3-based composites can improve their separation efficiency and reusability [60, 61]. Overall, using Al_2O_3-based adsorbents for water purification has shown significant potential in removing contaminants.

Aluminium oxide nanoparticles (Al_2O_3 NPs) have emerged as promising candidates for environmental remediation due to their unique properties like High Surface Area, Enhanced adsorption capacity for increased adsorption of pollutants such as heavy metals, organic contaminants, and dyes and efficient removal of these pollutants from water and soil [62]. High Chemical Stability, resisting degradation under various environmental conditions and Long-term effectiveness: This stability ensures their long-term effectiveness in pollutant removal without compromising their structural integrity Zhang *et al.*, 2017 [63]. Studies have shown that Al_2O_3 NPs have relatively low toxicity to various organisms, making them suitable for environmental applications. Their biocompatibility reduces concerns about potential adverse effects on ecosystems. Al_2O_3 NPs can act as catalysts, accelerating the degradation of organic pollutants [64–66]. This catalytic activity can enhance the overall remediation process. Al_2O_3 is a relatively abundant and inexpensive material, making Al_2O_3 NPs a cost-effective option for environmental remediation. Al_2O_3 NPs can be modified with magnetic properties, enabling easy recovery from treated water or soil using magnetic separation. This recovery process minimizes waste generation and reduces the environmental footprint of remediation [67]. Research by Zhang *et al.* (2016) [68] has indicated potential toxicity in aquatic environments due to the release of Al_2O_3 NPs into water systems. Additionally, Keller *et al.* (2013) [69] emphasized the importance of evaluating the long-term effects of nanoparticle accumulation in soil and water, noting existing gaps in understanding their environmental behaviour and fate.

Promising further research is needed to optimise the synthesis and surface modification of these materials to achieve even better adsorption performance and make them more suitable for large-scale applications [70, 71]. With these research gaps, we reported high-quality Al_2O_3 nanoparticles using the low-cost ammonia Precipitation Method and their application in Cadmium removal. The ammonia Precipitation Method involves the addition of a concentrated solution of ammonia (NH_3) to the target solution containing metal ions by adjusting pH.

1. Materials and methods

1.1 Materials

All chemicals used in this study were of analytical reagent (AR) grade and procured from Renbaxy India. These include aluminium chloride hexahydrate ($AlCl_3.6H_2O$), ammonia solution (25%), ethanol (99%), and deionized water. The chemicals were used as received without further purification.

1.2 Experimental method

1.2.1 Synthesis of Al_2O_3 nanoparticles

Aluminium oxide nanoparticles were synthesized through a precipitation method. *In this method,* aluminium ions form insoluble metal hydroxide precipitates when exposed to an alkaline environment. By adjusting the pH of the solution with the addition of ammonia, the solubility of aluminium hydroxide lowered, causing it to precipitate out of the solution.

A 0.6 M solution of aluminium chloride was prepared by dissolving 7.24 g of $AlCl_3.6H_2O$ in 50 mL of ethanol under constant stirring at room temperature. The prepared aluminium chloride solution was added dropwise to a 25% ammonia solution under vigorous magnetic stirring. A white precipitate of aluminium hydroxide ($Al(OH)_3$) formed. The pH was maintained at an alkaline level throughout the process. The precipitated $Al(OH)_3$ was separated from the solution through filtration using a Whatman filter paper. The collected precipitate was washed repeatedly with ethanol to remove impurities. The washed residue was dried in an oven at 110 °C for 24 hours. Subsequently, the dried precipitate was calcined at 330 °C and 380 °C for 7 hours to obtain Al_2O_3 nanoparticles.

1.2.2 Characterizations

The obtained samples were characterized for Structural, optical, compositional and morphology characterizations. Structural, optical, compositional and morphology characterizations were performed for the nanocomposite samples. X-ray diffractograms were obtained using PAN analytical Empyrean with CuKα radiation of wavelength $\lambda = 0.15406$ nm in the scan range of 5°-80°; morphological studies of the nanocomposites were carried out by Jeol / Hitachi FE scanning electron microscope (SEM) and Jeol TEM transmission electron microscope, for TEM sample was dispersed in ethanol and placed on a Cu-grid carbon layer. FTIR spectra were obtained using FTIR spectrum-2, UV absorption was carried out using UV-visible Spectra-Perkin Elmer Lambda 25 in the 200-800 nm range, and PL spectra were obtained using Perkin Elmer LS55 spectrofluorometer under standard protocols.

2. Results and discussion

The synthesis of Al_2O_3 nanoparticles via the ammonia precipitation method is a cost-effective approach compared to conventional methods. This method utilizes readily available and inexpensive precursors such as aluminium chloride and ammonia, reducing the overall production costs. Additionally, the energy-efficient synthesis process, which involves moderate heating and avoids high-temperature treatments, further lowers the operational expenses. When compared to traditional adsorbents like activated carbon or ion-exchange resins, Al_2O_3 nanoparticles demonstrate superior adsorption capacity, thereby requiring smaller quantities to achieve effective pollutant remediation. This not only reduces material costs but also minimizes the frequency of replacement or regeneration of the adsorbent. Moreover, the reusable nature of Al_2O_3 nanoparticles, enabled by their high thermal and chemical stability, enhances their cost-effectiveness over multiple cycles of use. Overall, the integration of Al_2O_3 nanoparticles for pollutant remediation presents a promising and economically viable alternative to traditional methods, aligning with both environmental and financial sustainability goals [72–76].

2.1 Structural studies

The structural analysis of samples heated at various temperatures was carried out using x-ray diffractograms of the samples shown in Fig. 1(a) heated at temperatures 330 °C,

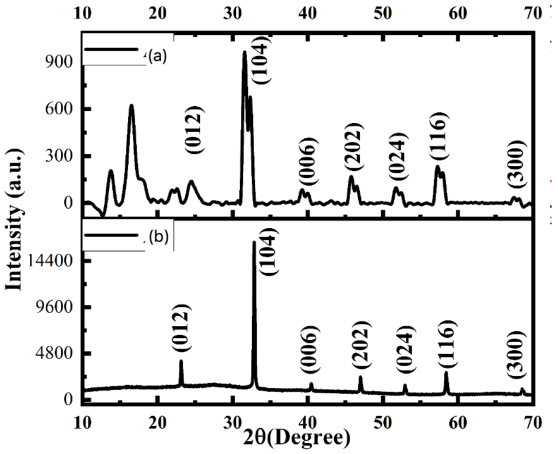


Figure 1. X. ray diffractograms of Al_2O_3 nanostructures heated at temperatures, (a) 330 °C, and (b) 380 °C.

and Fig. 1(b) 380 °C.

X-ray diffraction (XRD) analysis was employed to investigate the crystalline structure and phase purity of the synthesized Al_2O_3 nanoparticles [77–79]. The XRD pattern revealed the presence of many peaks, which are indexed and allocated with their corresponding places, such as 24.74°, 32.23°, 40.5°, 46°, 52.09°, 57°, and 68° can be well attributed to the crystal points (012), (104), (006), (202), (024), (116), and (300) of Al_2O_3 nanoparticle [80]. The phases of powder material correspond with γ- Al_2O_3 and it was confirmed with the database of JCPDS card no: 00-046-1212 [81].

The crystallite size was calculated using Debye Scherer's formula [82], and the average crystallite sizes of nanoparticles were determined from the XRD data.

$$D = \frac{0.9\lambda}{\beta \cos\theta} \tag{1}$$

where D is the crystallite size, β is the FWHM (full width at half maximum) intensity of the diffraction line in radians, λ is the CuKa=1.5406 X-ray wavelength, and θ is the Bragg's angle.

The average crystallite size, determined using the Scherrer equation, was found to be in the range of 46-68 nm, indicating the formation of nanocrystalline Al_2O_3 and no additional chemical impurities.

Williamson-Hall studies [73] were carried out using Eq. 2 and . 3 to determine the strain.

$$\beta_{hkl} = \beta_D + \beta_\varepsilon \tag{2}$$

where- β_{hkl} = FWHM, β_D = Crystallite size, and β_ε = strain induced broadening. The Williamson-Hall Equation can be simplified as follows:

$$\beta_{hkl} \cos_\theta = k\lambda/D + 4\varepsilon \sin\theta_{hkl} \tag{3}$$

To compute the crystallite size and microstrain of the Al_2O_3 nanoparticles, a relationship between $\beta_{hkl}\cos\theta$ and $\sin\theta$ is drawn for the prepared Sample and is illustrated in Fig. 2(a) at 330 °C and ((b) at 380 °C. The broadening of XRD peaks caused by the strain and the contribution of crystallite size can be summarized in Table 1. Williamson-Hall analysis revealed that the strain-induced broadening was minimal, suggesting good crystallinity of the nanoparticles. FTIR spectra of aluminium oxide were obtained as shown in Fig. 3.

Table 1. Particle size and strain calculation using Debye–Scherer formula and Williamson-Hall plots.

Sample Code	FWHM	D= $k\lambda/\beta\cos\theta$	Intercept	Strain
(a)	0/337118862	57/3530297	0/02525	-0/00845
(b)	0/015824551	3/176007193	0/45597	-0/18736

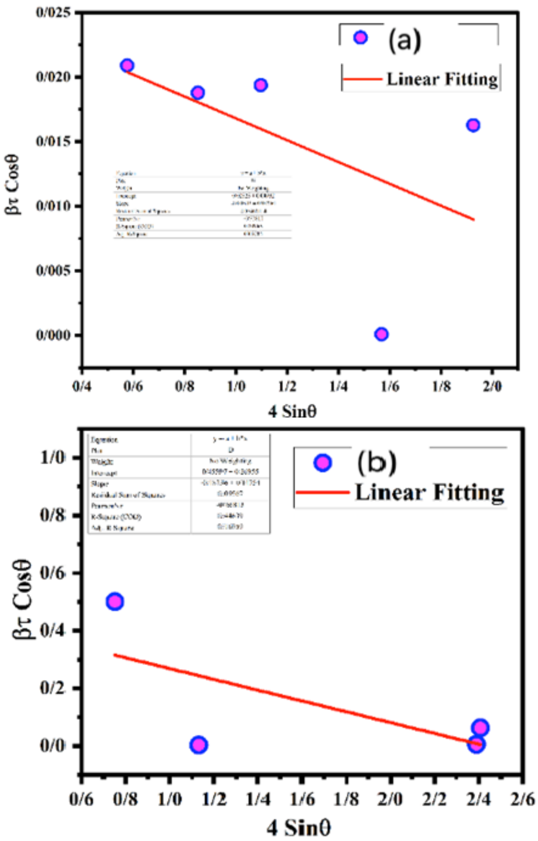


Figure 2. Williamson-Hall plots of Al_2O_3 nanostructures, (a) at 330 °C and, (b) at 380 °C.

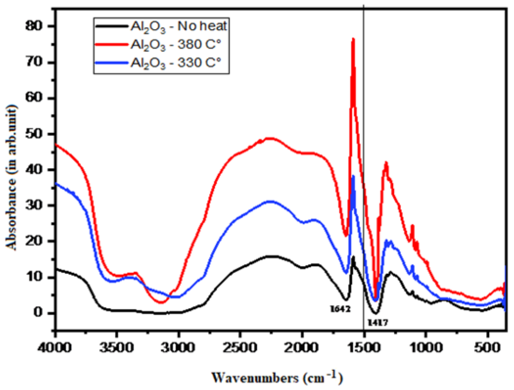


Figure 3. FT-IR spectrum of Aluminum oxide nanoparticles.

Table 2. FTIR stretching vibrations of Al_2O_3 Sample 1, Sample 2, Sample 3.

Functional Group corresponds	**Samples Frequency range(cm^{-1})**
O-H Stretching vibration	3400
O-H Bending Vibration	1600
Al-OH Stretching vibration	1417, 1450
Al-O Stretching vibration	400 - 1000
Al_2O_3	765 , 676

The peaks which appeared at 1417 cm^{-1} indicate the chloride ion of precursor and the plots at 1642 cm^{-1} and 3200 cm^{-1} assigned the bending vibration and stretching vibration of H-O-H molecule [81], this fig also shows the aluminium oxide nanoparticles without heat has low absorbance and the one after heated has high transmittance and now see the second plots which show the peak at 620 cm^{-1} attributes to the Al-O stretching bong the peak at 1141 cm^{-1} assigned the vibrational mode of ion the peak at 1447 contribute the vibration of Al-O-Al have been seen and the peaks at 1663 cm^{-1} and 3560 cm^{-1} both shows the stretching and bending vibrational of water(-OH) molecules from here also we can say that heating is effective on these compounds. FTIR peaks are shown in Table 2.

2.2 Morphological studies (FESEM)

Fig. 4. shows FESEM micrograph images of the calcined alumina samples (a) at 330 °C and (b) at 380 °C. Particles are spherical in shape (d=57 nm) at both temperatures. The FE-SEM study of the particle size distribution revealed that most particles are in the 35nm-55nm range. The majority of the nanoparticles are fairly uniform in size and have defined proportions, which was further confirmed by the size distribution [82–84].

2.3 Absorption studies

The UV-Vis spectra for the investigated samples, presented in Figure 5, span the wavelength range from 200nm to 700nm. Notably, all samples exhibit prominent absorption features within both the UV and visible regions, indicative of their unique electronic transitions. In the UV region, distinct absorption peaks are consistently observed around 250 nm across all temperature conditions, highlighting a robust absorption capability in this spectral range. Furthermore, in the visible region [85], a notable absorption peak is consistently located around 460nm. Upon closer examination, a subtle enhancement in absorption is discernible as the temperature increases. This temperature-dependent trend is particularly evident in higher temperature regimes, suggesting a responsive behaviour of the samples to thermal conditions. The observed improvement in absorption at elevated temperatures underscores the dynamic nature of the electronic transitions within the samples, showcasing a potential avenue for temperature-induced modulation of their optical properties. These findings not only underscore the significance of temperature in influencing absorption characteristics but also pave the way for exploring the intricate interplay between temperature and electronic transitions in the studied samples. The consistent absorption peaks at specific wavelengths further provide valuable insights into the

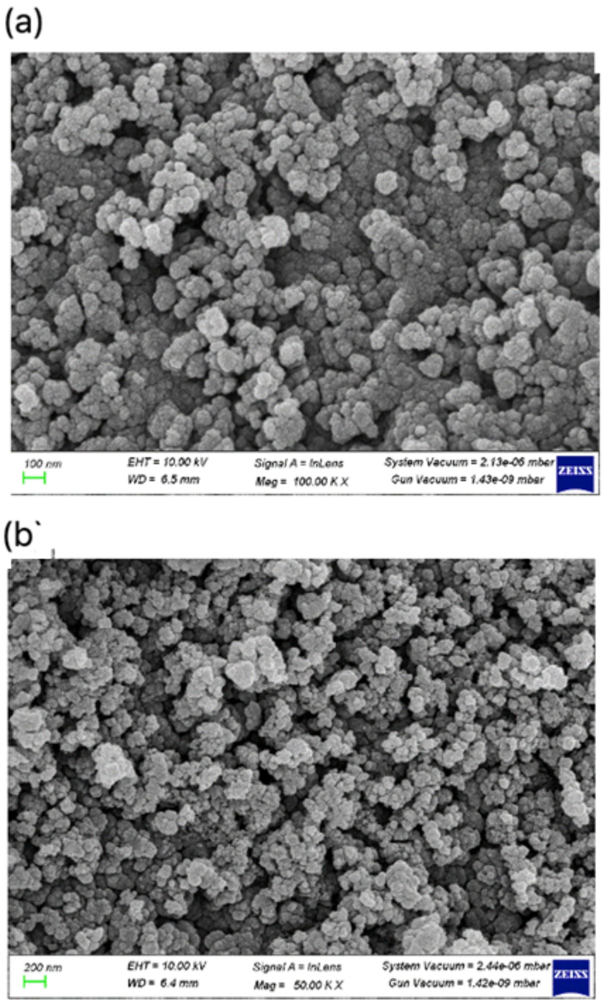


Figure 4. FE-SEM micrograph of alumina nanoparticles (a) at 330 °C and (b) 380 °C.

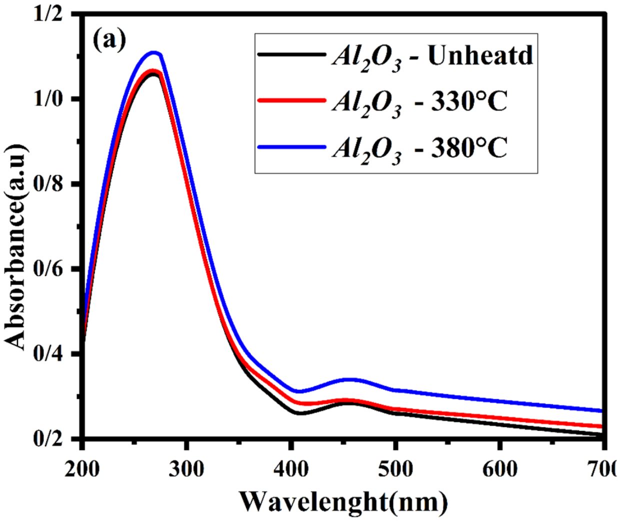


Figure 5. UV-Vis spectra of Aluminum oxide nanoparticles at alumina nanoparticles, (a) at 330 °C and, (b) 380 °C.

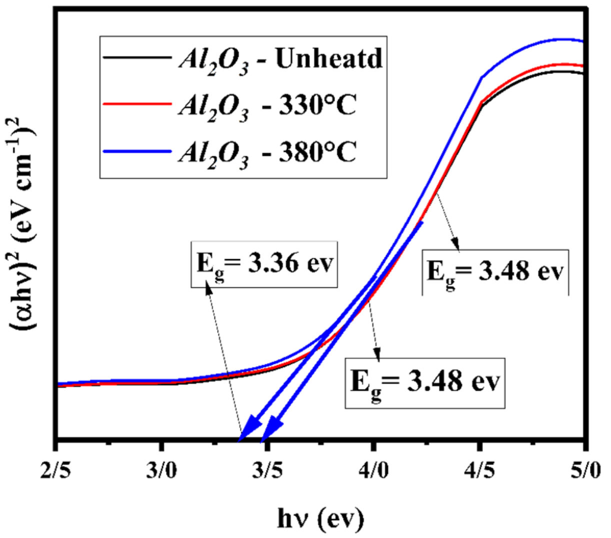


Figure 6. Tauc plots for alumina nanoparticles (a) at 330 °C and, (b) 380 °C.

molecular or structural features responsible for the observed optical behaviour.

To calculate the bandgap the Tauc plots between $h\nu$ vs $(\alpha h\nu)^2$ obtained are shown in Fig. 6. For a high temperature-heated sample shift in band gap to lower temperature is observed. Band gap for samples of unheated alumina, samples (a) heated to 330 degrees, and (b) samples heated to 380 degrees, observed were 3.48 eV, 3.48 eV, and 3.36 eV, respectively.

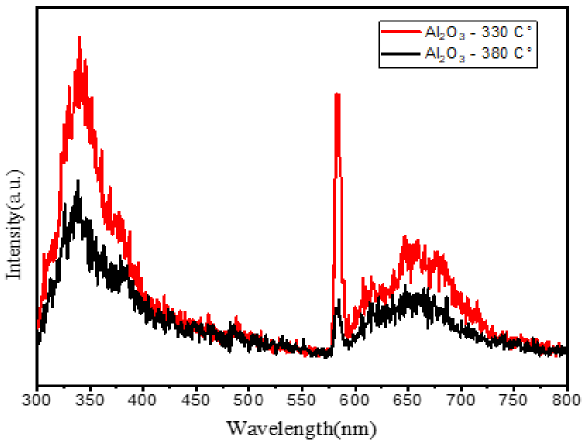
2.4 Photoluminescence (PL) spectroscopy

PL spectra for Aluminium oxide nanoparticles heated (a) at 330 °C and, (b) 380 °C and shown in Fig. 7.

The Aluminum oxide nanoparticles synthesized at 330 °C exhibit a strong peak in the range of 300 nm-400 nm, followed by a sharp at 589nm and a broad peak in 640 nm -680 nm range in the visible region. A similar emission pattern was observed for all Al_2O_3 nanoparticle samples, characterised by a broad emission band in the 300-570 nm region, a narrower peak around 600 nm, and another broad band centred at 650 nm [86]. These results collectively indicate commendable luminescent properties of the synthesized Al_2O_3 nanoparticles within the visible region. The broad emission band in the UV-visible region could be attributed to defect-related luminescence, arising from oxygen vacancies or other structural imperfections within the Al_2O_3 lattice. The sharp peak at 589 nm might be associated with specific impurity levels or surface states. Surface defects such as unsaturated bonds or dangling bonds can act as radiative recombination centres. These defects can trap charge carriers and contribute to the emission in the visible region, often influencing the intensity and position of the observed peaks. The red emission band (640-680 nm) is attributed to deep-level defect centres, such as oxygen vacancies or interstitial atoms, which facilitate radiative recombination, contributing to the visible region luminescence. This emission is indicative of recombination processes involving more deeply localized defect states, often related to the long-wavelength tail in the emission spectrum. These mechanisms collectively contribute to the commendable luminescent properties of the synthesized Al_2O_3 nanoparticles within the visible region.

2.5 Elimination of Cadmium from Water using Aluminum oxide nanoparticles.

To evaluate the cadmium (Cd(II)) removal efficiency of the synthesized Al_2O_3 nanoparticles, batch adsorption experiments were conducted. Stock solutions of Cd(II) (1000 mg/L) were prepared using $CdCl_2.H_2O$ (Merck) and diluted to obtain working solutions. A fixed volume (50 mL) of Cd (II) solution was mixed with varying amounts of Al_2O_3 nanoparticles (1 mg and 2 mg) in batch reactors. The mixtures were agitated at room temperature with the help of a shaker for 70 min., followed by filtration. The residual Cd (II) concentration in the filtrate was determined using UV-Visible spectroscopy. Fig. 8 shows UV vis spectra. UV-Visible spectroscopy analysis revealed a significant decrease



(a)

Figure 7. PL spectra of alumina nanoparticles (a) at 330 °C, and (b) 380 °C.

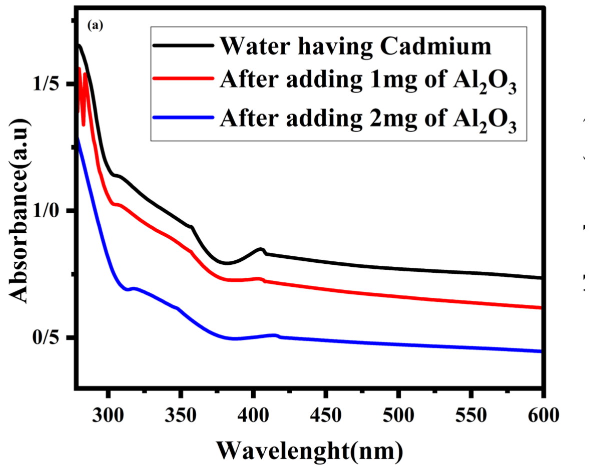


Figure 8. UV-Vis spectra of water having cadmium treated with various concentrations of Aluminum oxide nanoparticles.

in the absorption peaks of Cd(II) at 310 nm and 415 nm upon the addition of Al_2O_3 nanoparticles, indicating effective Cd(II) removal. The results demonstrated the potential of the synthesized Al_2O_3 nanoparticles as a promising adsorbent for cadmium removal from aqueous solutions.

To contextualize the performance of aluminium oxide nanoparticles in cadmium removal, it is essential to compare them with other existing adsorbents. Traditional adsorbents such as activated carbon, zeolites, and clay minerals have been widely used for heavy metal removal due to their high surface areas and affinity for metal ions. However, these materials often suffer from limitations such as lower adsorption capacities and slower kinetics. For instance, a study by Gupta *et al.* (2016) [87] demonstrated that activated carbon, while effective, requires higher dosages to achieve comparable removal rates and has slower adsorption kinetics compared to nanomaterials. Another study by Wang *et al.* (2018) [88] found that zeolites, despite their high surface area, exhibit lower cadmium ion removal efficiency due to limited active sites and pore blockage issues. Similarly, research by Liu *et al.* (2017) [89] indicated that clay minerals, although cost-effective, have lower adsorption capacities and can suffer from leaching of adsorbed metals under certain conditions. In contrast, aluminium oxide nanoparticles exhibit superior adsorption performance due to their high surface area, well-defined pore structure, and strong affinity for cadmium ions. Studies have shown that aluminium oxide nanoparticles can achieve higher removal efficiencies at lower dosages compared to conventional adsorbents. Their faster kinetics allow for more rapid removal of cadmium ions, and their regeneration and reuse have been demonstrated to be more straightforward and efficient, maintaining high efficacy over multiple cycles. Overall, aluminium oxide nanoparticles present a promising alternative to conventional adsorbents for cadmium removal, offering enhanced performance and potential cost benefits. However, further research is necessary to address scalability and long-term stability, ensuring their practical application in large-scale environmental remediation efforts.

2.6 Scalability of the ammonia precipitation method for the large-scale synthesis

The scalability of the ammonia precipitation method for the large-scale synthesis of aluminium oxide nanoparticles is an important consideration for industrial applications. While this method is effective for laboratory-scale production, scaling up presents several challenges. One major challenge is maintaining uniform particle size and distribution, which can be difficult when increasing batch volumes. Additionally, the control of reaction parameters such as pH, temperature, and concentration becomes more complex at larger scales, potentially affecting the quality and consistency of the nanoparticles produced. To address these challenges, advanced mixing technologies and continuous flow reactors can be employed to ensure consistent reaction conditions and uniform precipitation. Optimizing the rate of ammonia addition and ensuring thorough mixing can help maintain homogeneity across larger volumes. Moreover, implementing real-time monitoring and control systems can provide precise regulation of reaction parameters, enhancing the reproducibility of the synthesis process. Further research into the development of scalable protocols and pilot-scale experiments is necessary to fully realize the potential of the ammonia precipitation method for industrial-scale production of aluminium oxide nanoparticles. By addressing these scalability challenges, the method can be refined to meet the demands of large-scale applications, thereby expanding its utility in various industrial sectors.

3. Conclusion

This study successfully synthesized aluminium oxide nanoparticles using a cost-effective ammonia precipitation method, achieving effective cadmium removal from wastewater. The nanoparticles demonstrated a crystalline structure and exhibited favourable luminescence behaviour in the visible region. XRD analysis confirmed the formation of aluminium oxide nanoparticles with a rhombohedral structure. The UV-Vis spectrophotometer analysis indicated a significant increase in absorption intensity, highlighting the efficacy of aluminium oxide nanoparticles as an adsorbent for cadmium removal from wastewater. The results suggest that aluminium oxide nanoparticles are promising candidates for water purification due to their high surface area, stability, and low toxicity. Compliance with regulatory standards and guidelines is paramount for the safe and effective application of Al_2O_3 NPs in water treatment. Proactive measures to address these regulatory requirements, including standardized testing methods and transparent reporting, are essential to ensure the sustainable and responsible use of Al_2O_3 NPs in water treatment processes. Future research should explore the removal of other heavy metals and pollutants using aluminium oxide nanoparticles. Investigating the reusability and long-term stability of the nanoparticles will provide insights into their practical applications. Additionally, surface modification of the nanoparticles could enhance their adsorption capacity and selectivity for different contaminants. The development of composite materials incorporating aluminium oxide nanoparticles could further improve their performance in water treatment applications.

Acknowledgement
The authors are thankful to MPCST, Bhopal for Funding this research grant and ITM University Gwalior for providing a seed money grant for this project.

Authors contribution
Authors were contributed equally to prepare and writing the manuscript.

No conflict of interest
On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data availability statement
The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Y. C. Goswami, S. Begzaad, and J. B. Kaundal. "Highly luminescent cu-doped sno$_2$ nanocomposites and their photocatalytic application as excellent methylene dye removal.". *J. Adv. Sci. Res.*, 13:94–103, 2022.
DOI: https://doi.org/10.55218/JASR.202213417.

[2] F. Westall and A. Brack. "The importance of water for life.". *Space Sci. Rev.*, 214(2):50, 2018.
DOI: https://doi.org/10.1007/s11214-018-0476-7.

[3] A. Issakhov, A. Alimbek, and Y. Zhandaulet. "The assessment of water pollution by chemical reaction products from the activities of industrial facilities: numerical study.". *J. Clean. Prod.*, 282(1): 125239, 2021.
DOI: https://doi.org/10.1016/j.jclepro.2020.125239.

[4] S. M. Abdelbasir and A. E. Shalan. "An overview of nanomaterials for industrial wastewater treatment.". *Korean J. Chem. Eng.*, 36(8): 1209–1225, 2019.
DOI: https://doi.org/10.1007/s11814-019-0306-y.

[5] J. Archer. "The water you drink: how safe is it.". *ABC Books.*, 1996.

[6] Y. C. Goswami, R. Bisauriya, A. A. Hlaing, T. T. Moe, and D. Aryanto. "Highly fluorescent zns encapsulated flexible nanocellulose grown by two-step hydrothermal route and their optical, structural and morphological characterization.". *Mat. Sci. and Engg.*, B 296:116708, 2023.
DOI: https://doi.org/10.1016/j.mseb.2023.116708.

[7] J. B. Kaundal, Y. C. Goswami, and R. Sharma. "Optically important transparent syndiotactic polystyrene/fes composites grown by low sol-gel route.". *Orient J. Chem.*, 38(3), 2022.
DOI: https://doi.org/10.13005/ojc/380330.

[8] S. Nagaich and Y. C. Goswami. "Shor's algorithm for quantum numbers using matlab simulator, fifth international conference on advanced computing & communication technologies, haryana, india.". 2015:165–168, 2015. URL 10.1109/ACCT.2015.16.

[9] R. B. Johnston and P. R. Johnston. "The politics of healing: histories of alternative medicine in twentieth-century north america.". *Routledge*, 2006.

[10] V. Kumar, P. Rajaram, and Y. C. Goswami. "Sol-gel synthesis of sno$_2$/cds heterostructures using various cd:s molar ratio solutions and its application in photocatalytic degradation of organic dyes.". *J. Mater Sci.: Mater. Electron.*, 28:9024–9031, 2017.
DOI: https://doi.org/10.1007/s10854-017-6634-y.

[11] G. Genchi, M. S. Sinicropi, G. Lauria, A. Carocci, and A. Catalano. "The effects of cadmium toxicity.". *Int. J. Environ. Res. Public Health.*, 17(11):3782, 2020.
DOI: https://doi.org/10.3390/ijerph17113782.

[12] M. Koller and H. M. Saleh. "Introductory chapter: introducing heavy metals.". *Heavy Metals. InTech.*, 2018.
DOI: https://doi.org/10.5772/intechopen.74783.

[13] F. Westall and A. Brack. "The importance of water for life.". *Space Sci. Rev.*, 214(2), 2018.
DOI: https://doi.org/10.1007/s11214-018-0476-7.

[14] J. B. Kaundal, R. K. Tiwari, and Y. C. Goswami. "Hydrothermally grown cds-embedded graphene oxide nanocomposites with enhanced optical properties.". *Emer. Mate. Res.*, 12(3):1–5, 2023.
DOI: https://doi.org/10.1680/jemmr.22.00019.

[15] Y. C. Goswami, J. B. Kaundal, and S. Begzaad. "Photocatalytic degradation of methyl red dye using highly efficient zno/cds hierarchical heterostructures under white led.". *J Iran. Chem. Soc.*, 20: 1681–1697, 2023.
DOI: https://doi.org/10.1007/s13738-023-02789-8.

[16] R. B. Johnston and P. R. Johnston. "The politics of healing: histories of alternative medicine in twentieth-century north america.". *Routledge*, 2006.
DOI: https://doi.org/10.4324/9780203506073.

[17] R. Mohapatra, J. B. Kaundal, and Y. C. Goswami. "Synthesis of optically important transparent sns/ps composite films through chemical route and their photocatalytic applications.". *J. Ovonic. Res.*, 18(3): 343–355, 2022.
DOI: https://doi.org/10.15251/JOR.2022.183.343.

[18] A. E. Charkiewicz, W. J. Omeljaniuk, K. Nowak, M. Garley, and J. Nikliński. "Cadmium toxicity and health effects.". *A Brief Summary. Mol.*, 28:6620, 2023.
DOI: https://doi.org/10.3390/molecules28186620.

[19] R. Singh, D. Kumar, Y. C. Goswami, and R. Sharma. "Synthesis, spectral studies and quantum-chemical investigations on s-benzyl β-n-(4-biscyno diethylamino phenylmethylene) dithiocarbazate.". *Arab. J. Chem.*, 12(7):1537–1544, 2019.
DOI: https://doi.org/10.1016/j.arabjc.2014.10.022.

[20] Y. C. Goswami, Goswami Ranjana, and T. K. Chirova. "Highly effective antifungal and antibacterial properties of zno, zns, fes and sno$_2$ nanoparticles against various fungal and bacterial isolates.". *Orient. J. Chem.*, 40(2):492, 2024. URL 10.13005/ojc/400222.

[21] C. V. Lakshminarayanan and I. Bhattacharya. "Adv. in optical science and engineering.". *Springer Proc. Phys.*, 166:533–539, 2014.

[22] M. Qa and K. Ms. "Effect on human health due to drinking water contaminated with heavy metals.". *J. Pollut. Eff. Control.*, 05(01), 2016.
DOI: https://doi.org/10.4172/2375-4397.1000179.

[23] J. K. Lee, Y. Yoon, J. H. Kim, and S. H. Kim. "Application of advanced oxidation processes for wastewater treatment.". *Sustain.*, 11(8):2195, 2019.
DOI: https://doi.org/10.3390/w11020205.

[24] Z. Aksu and I. A. Isoglu. "Bio-remediation of water pollutants by microorganisms.". *Chemosphere.*, 272:129622, 2021.
DOI: https://doi.org/10.3389/fagro.2023.1183691.

[25] X. Wang, Y. Zheng, and J. Shen. "Recent advances in the application of coagulation/flocculation for wastewater treatment.". *Environ. Eng. Sci.*, 35(3):209–223, 2018.
DOI: https://doi.org/10.1016/j.jclepro.2022.131133.

[26] M. Jia, M. U. Farid, J. A. Kharraz, N. M. Kumar, S. S. Chopra, A. Jang, J. Chew, S. K. Khanal, G. Chen, and A. An. "Nanobubbles in water and wastewater treatment systems: small bubbles making big difference.". *Water Res.*, 245:120613, 2023.
DOI: https://doi.org/10.1016/j.watres.2023.120613.

[27] Y. C. Goswami, R. Bisauriya, A. A. Hlaing, T. T. Moe, J. B. Kaundal, D. Aryanto, and R. Yudianti. "Enhancing photocatalytic performance of sno2/zns nanocomposites synthesized via dual-step precipitation and ultrasonicated hydrothermal route.". *Curr. Appl. Phys.*, 68:275–283, 2024.
DOI: https://doi.org/10.1016/j.cap.2024.10.011.

[28] N. Kumar, L. P. Purohit, and Y. C. Goswami. "Spin coating of zns nanostructures on filter paper and their characterization.". *Phys. E Low-Dimens. Syst. Nanostruct.*, 83:333–338, 2016.
DOI: https://doi.org/10.1016/j.physe.2016.04.025.

[29] N. Kumar, L. P. Purohit, and Y. C. Goswami. "Synthesis of cu-doped zns nanostructures on flexible substrate using low-cost chemical method.". *AIP Conf. Proc.*, 1675:020030, 2015.
DOI: https://doi.org/10.1063/1.4929188.

[30] S. S. Fiyadh, M. A. Alsaadi, W. Z. Jaafar, M. K. Alomar, S. S. Fayaed, N. S. Mohd, L. S. Hin, and A. El-Shafie. "Review on heavy metal adsorption processes by carbon nanotubes.". *J. Clean. Prod.*, 230: 783–793, 2019.
DOI: https://doi.org/10.1016/j.jclepro.2019.05.154.

[31] A. A. Yaqoob. "Role of nanomaterials in the treatment of wastewater: a review.". *Water*, 12(2), 2020.
DOI: https://doi.org/10.3390/w12020495.

[32] R. Vinayagam, V. Nagendran, L. C. Goveas, M. K. Narasimhan, T. Varadavenkatesan, N. Chandrasekar, and R. Raja Selvaraj. “Structural characterization of marine macroalgae derived silver nanoparticles and their colorimetric sensing of hydrogen peroxide.”. *Mat. Chem. Phys.*, 313:128787, 2024.
DOI: https://doi.org/10.1016/j.matchemphys.2023.1287.

[33] R. Selvaraj, V. Nagendran, T. Varadavenkatesan, L. C. Goveas, and R. Vinayagam. “Stable silver nanoparticles synthesis using tabebuia aurea leaf extract for efficient water treatment: a sustainable approach to environmental remediation.”. *Chem. Engg. Res. Des.*, 208:456–463, 2024.
DOI: https://doi.org/10.1016/j.cherd.2024.07.012.

[34] T. Varadavenkatesan, V. Nagendran, R. Vinayagam, L. C. Goveas, and R. Selvaraj. “Effective degradation of dyes using silver nanoparticles synthesized from thunbergia grandiflora leaf extract.”. *Biores. Tech. Rep.*, 27:101914, 2024.
DOI: https://doi.org/10.1016/j.biteb.2024.101914.

[35] S. A. Ansari and N. Parveen. “Enhanced photocatalytic degradation of organic pollutants using iron lanthanum oxide nanoparticles.”. *Mat. Sci. Exp.*, 1(1):28–32, 2024.
DOI: https://doi.org/10.69626/mse.2024.0028.

[36] S. A. Ansari. “Elemental semiconductor red phosphorus/zno nanohybrids as high-performance photocatalysts.”. *Ceram. Int.*, 49:17746–17752, 2023.
DOI: https://doi.org/10.1016/j.ceramint.2023.02.140.

[37] N. Parveen, F. O. Alqahtani, G. M. Alsulaim, S. A. Alsharif, K. M. Alnahdi, H. A. Alali, M. M. Ahmad, and S. A. Ansari. “Emerging mesoporous polyacrylamide/gelatin–iron lanthanum oxide nanohybrids towards the antibiotic drugs removal from wastewater.”. *Nanomat.*, 13(21):2835, 2023.
DOI: https://doi.org/10.3390/nano13212835.

[38] S. A. Ansari, N. Parveen, G. M. Alsulaim, A. A. Ansari, S. A. Alsharif, K. M. Alnahdi, H. A. Alali, and V. R. M. Reddy. “Emerging nio-rgo nanohybrids for antibiotic pollutant degradation under visible-light irradiation.”. *Surf. Int.*, 40:103078, 2023.
DOI: https://doi.org/10.1016/j.surfin.2023.103078.

[39] H. I. Alrayzan, S. A. Ansari, and N. Parveen. “Fabrication of asymmetric supercapacitor device based on nickel hydroxide electrode-graphene assembly.”. *J. Nanoelectron. Optoelectron.*, 17(3):536–543, 2022.
DOI: https://doi.org/10.1166/jno.2022.3246.

[40] B. Azari, A. Pourahmad, B. Sadeghi, and M. Mokhtary. “J. Coord. Chem.”. *Int. J. Nano Dimens.*, 76(2):219–231, 2023.
DOI: https://doi.org/10.1080/00958972.2023.2166408.

[41] B. Sadeghi and R. A. R. Vahdati. “”. *Appl. Surf. Sci.*, 258(7):3086–3088, 2012.
DOI: https://doi.org/10.1016/j.apsusc.2011.11.042.

[42] V. N. Thekkudan, V. K. Vaidyanathan, S. K. Ponnusamy, C. Charles, S. Sundar, D. Vishnu, S. Anbalagan, V. K. Vaithyanathan, and S. Subramanian. “Review on nanoadsorbents: a solution for heavy metal removal from wastewater.”. *IET Nanobiotechnol.*, 11(3):213–224, 2017.
DOI: https://doi.org/10.1049/iet-nbt.2015.0114.

[43] N. Thirumalaivasan, P. Venkatesan, P. S. Lai, and S. P. Wu. “In vitro and in vivo approach of hydrogen-sulfide-responsive drug release driven by azide-functionalized mesoporous silica nanoparticles.”. *ACS Appl. Biomat.*, 2:3886–3896, 2019.
DOI: https://doi.org/10.1021/acsabm.9b00481.

[44] E. Gayathiri, P. Prakash, T. Pratheep, R. Ramasubburayan, N. Thirumalaivasan, A. Gaur, R. Govindasamy, and K. R. R. Rengasamy. “Biosurfactants from lactic acid bacteria: an in-depth analysis of therapeutic properties and food formulation.”. *Crit. Rev. Food Sci. Nutr.*, 64(30):10925–10949, 2023.
DOI: https://doi.org/10.1080/10408398.2023.2230491.

[45] P. Venkatesan, N. Thirumalaivasan, H. P. Yu, P. S. Lai, and S. P. Wu. “Redox stimuli delivery vehicle based on transferrin-capped msnps for targeted drug delivery in cancer therapy.”. *ACS Appl. Bio Mater.*, 2(4):1623–1633, 2016.
DOI: https://doi.org/10.1021/acsabm.9b00036.

[46] V. Murugesan, M. Govindarasu, S. Manoharadas, S. Pandiaraj, M. Thiruvengadam, R. Govindasamy, and M. Vaiyapuri. “Combinatorial anticancer effects of multi metal ion and drug substitute with hydroxyapatite coatings on surgical grade 316lss stainless steel alloys towards biomedical applications.”. *J. Mater. Res. Technol.*, 27: 7244–7258, 2023.
DOI: https://doi.org/10.1016/j.jmrt.2023.11.036.

[47] R. Thandavamoorthy, V. R. Krishnan, M. I. Reddy, S. A. Obaid, S. A. Alharbi, and M. A. Kalam. “Studies on mechanical and morphological behaviors of banyan/kevlar fibers reinforced mgo particulates hybrid aliphatic epoxy composite.”. *Int. J. Adv. Manuf. Tech.*, 130: 1–8, 2023.
DOI: https://doi.org/10.1007/s00170-023-11852-w.

[48] P. Punia, M. K. Bharti, S. Chalia, R. Dhar, B. Ravelo, P. Thakur, and A. Thakur. “Recent advances in synthesis, characterization, and applications of nanoparticles for contaminated water treatment- a review.”. *Ceram. Int.*, 47(2):1526–1550, 2021.
DOI: https://doi.org/10.1016/j.ceramint.2020.09.050.

[49] D. Pal, G. Singh, Y. C. Goswami, and V. Kumar. “Synthesis of randomly oriented self-assembled cus nanorods by co-precipitation route.”. *J. Mater. Sci.: Mater. Electron.*, 30:15700–15704, 2019.
DOI: https://doi.org/10.1007/s10854-019-01953-2.

[50] R. Sharma, R. Singh, Y. C. Goswami, V. Kumar, and D. Kumar. “Highly luminescent cds nanoparticles synthesized using microwave irradiation of dithiocarbazate ligand as a single molecular precursor source.”. *J. Aust. Ceram. Soc.*, 57:697–703, 2021.
DOI: https://doi.org/10.1007/s41779-021-00563-8.

[51] Y. C. Goswami, R. Sharma, and P. Rajaram. “Growth of cds nanostructures by new sol-gel route and its optical characterization.”. *Nanotech. Nanosci.*, 2(1):38–41, 2014.

[52] Y. C. Goswami, V. Kumar, R. Sharma, and R. Singh. “Synthesis of cds/cdse core/shell ultra-small nanostructures using new microwave-assisted ultrasonic sol-gel route.”. *AIP Conference Proceedings*, 1591(1):414–416, 2014.
DOI: https://doi.org/10.1063/1.4872622.

[53] H. Lu, J. Wang, M. Stoller, T. Wang, Y. Bao, and H. Hao. “An overview of nanomaterials for water and wastewater treatment.”. *Adv. Mater. Sci. Eng.*, 4964828:1–10, 2016.
DOI: https://doi.org/10.1155/2016/4964828.

[54] S. Mura, Y. Jiang, I. Vassalini, A. Gianoncelli, I. Alessandri, G. Granozzi, L. Calvillo, N. Senes, S. Enzo, P. Innocenzi, and L. Malfatti. “Graphene oxide/iron oxide nanocomposites for water remediation.”. *ACS Appl. Nano Mat.*, 1(12):6724–6732, 2018.
DOI: https://doi.org/10.1021/acsanm.8b01540.

[55] P. Xu, Guang, G. M. Zeng, D. L. Huang, C. Lai, M. H. Zhao, Z. Wei, N. J. Li, C. Huang, and G. X. Xie. “Adsorption of pb(ii) by iron oxide nanoparticles immobilized phanerochaete chrysosporium: equilibrium, kinetic, thermodynamic and mechanisms analysis.”. *Chem. Eng. J.*, 203:423–431, 2012. URL 10.1016/j.cej.2012.07.048.

[56] S. T. Yang, S. Chen, Y. Chang, A. Cao, Y. Liu, H. Wang, and Y. Liu. “Removal of methylene blue from aqueous solution by graphene oxide.”. *J. Colloid Interface Sci.*, 359(1):24–29, 2011.
DOI: https://doi.org/10.1016/j.jcis.2011.02.064.

[57] J. Saleem, H. M. A. Asghar, M. B. Tahir, M. Batool, S. Saeed, M. R. Shah, and M. Siddiq. “Carbon nanotubes: a promising material for wastewater treatment.”. *J. Mol. Liquids*, 309:113068, 2020.
DOI: https://doi.org/10.1088/1742-6596/61/1/140.

[58] K. Wang, X. Yang, L. Zhang, C. Chen, Y. Chen, and J. Zhang. “Efficient removal of organic pollutants from water using metal–organic frameworks (mofs): a review.”. *J. Hazard. Mater.*, 341:298–318, 2018.
DOI: https://doi.org/10.1016/j.chemosphere.2021.131393.

[59] G. Lin, B. Zeng, J. Li, Z. Wang, S. Wang, T. Hu, and L. Zhang. “A systematic review of metal organic frameworks materials for heavy metal removal: synthesis, applications and mechanism.”. *Chem. Eng. J.*, 460:2141710, 2023.
DOI: https://doi.org/10.1016/j.cej.2023.141710.

[60] A. Z. Ziva, Yuni, K. Suryana, Y. S. Kurniadianti, R. Ragadhita, A. B. D. Nandiyanto, and T. Kurniawan. “Recent progress on the production of aluminum oxide (al$_2$o$_3$) nanoparticles: a review.”. *Mech. Eng. Soc. Ind.*, 1(2):54–77, 2021.
DOI: https://doi.org/10.31603/mesi.5493.

[61] A. A. Mohammed, Z. T. Khodair, and A. A. Khadom. “Preparation, characterization and application of al$_2$o$_3$ nanoparticles for the protection of boiler steel tubes from high temperature corrosion.”. *Ceram. Int.*, 46(17):26945–26955, 2020.
DOI: https://doi.org/10.1016/j.ceramint.2020.07.172.

[62] K. Ravindhranath and M. Ramamoorty. “Nano aluminum oxides as adsorbents in water remediation methods: a review.”. *RASAYAN J. Chem.*, 10(3):716–722, 2017.
DOI: https://doi.org/10.7324/RJC.2017.1031762.

[63] Z. Zhang, Y. Zhu, H. Asakura, B. Zhang, J. Zhang, M. Zhou, Y. Han, T. Tanaka, A. Wang, T. Tao Zhang, and N. Yan. “Thermally stable single atom pt/m-al$_2$o$_3$ for selective hydrogenation and cO oxidation.”. *Nat Comm.*, 8:16100, 2017.
DOI: https://doi.org/10.1038/ncomms16100.

[64] S. Mahdavi, M. Jalali, and A. Afkhami. “Heavy metals removal from aqueous solutions by al$_2$o$_3$ nanoparticles modified with natural and chemical modifiers.”. *Clean Technol. Environ. Policy.*, 17:85–102, 2015.
DOI: https://doi.org/10.1007/s10098-014-0764-1.

[65] A. I. Alghriany, H. M. EL-din, A. M. Omar, M. Mahmoud, and M. M. Atia. “Assessment of the toxicity of aluminum oxide and its nanoparticles in the bone marrow and liver of male mice: ameliorative efficacy of curcumin nanoparticles.”. *ACS Omega*, 7(16): 13841–13852, 2022.
DOI: https://doi.org/10.1021/acsomega.2c00195.

[66] M. A. Awad, R. Jalab, A. Benamor, M. S. Nasser, M. M. Ba-Abbad, M. El-Naas, and A. W. Mohammad. “Adsorption of organic pollutants by nanomaterial-based adsorbents: an overview.”. *J. Mol. Liq.*, 301:112335, 2020.
DOI: https://doi.org/10.1016/j.molliq.2019.112335.

[67] G. Martínez, M. Merinero, M. Pérez-Aranda, E. M. Pérez-Soriano, T. Ortiz, B. Begines, and A. Alcudia. “Environmental impact of nanoparticles’ application as an emerging technology: a review.”. *Mat.*, 14(1):166, 2020.
DOI: https://doi.org/10.3390/ma14010166.

[68] H. Zhang, X. He, Z. Zhang, P. Zhang, Y. Li, and Y. Ma. “Toxicity of aluminum oxide nanoparticles to aquatic organisms: a review.”. *Desalin. Water Treat.*, 195:286–296, 2020.
DOI: https://doi.org/10.5004/dwt.2020.25882.

[69] A. A. Keller, A. Lazareva, S. Suh, J. Keller, and T. Theis. “Comparative analysis of environmental impacts of manufactured nanomaterials.”. *Env. Sci. Tech.*, 47(17):8689–8699, 2013.
DOI: https://doi.org/10.1021/ez400106t.

[70] A. Sreya and C. K. Chidambaran. “An overview on the applications and environmental risk assessment of nanomaterials in aquatic organisms.”. *J. Biol. Nat.*, 13(1):1–30, 2021.

[71] X. Zhu, Q. Jin, and Z. Ye. “Life cycle environmental and economic assessment of alumina recovery from secondary aluminium dross in china.”. *J. Cleaner Prod.*, 277:123291, 2020.
DOI: https://doi.org/10.1016/j.jclepro.2020.123291.

[72] S. Liu, Y. Zhang, X. Wu, H. Zhao, and X. Guo. “Enhanced removal of heavy metal ions from aqueous solutions by kaolin modified with ionic liquid and aluminium oxide.”. *J. Hazard. Mater.*, 299:703–712, 2015.
DOI: https://doi.org/10.1016/j.jhazmat.2015.07.070.

[73] L. Hou, Q. Zhang, J. Han, X. Li, and P. Wang. “Adsorption of methylene blue onto mesoporous aluminium oxide: equilibrium, kinetics, and thermodynamics.”. *Matls.*, 6:11, 2018.
DOI: https://doi.org/10.3390/ma11081374.

[74] H. Li, V. L. Budarin, J. H. Clark, M. North, and X. Wu. “Rapid and efficient adsorption of methylene blue dye from aqueous solution by hierarchically porous, activated starbons: mechanism and porosity dependence.”. *J. Hazard. Mat.*, 436:129174, 2022.
DOI: https://doi.org/10.1016/j.jhazmat.2022.129174.

[75] H. Zhang, X. He, Z. Zhang, P. Zhang, Y. Li, and Y. Ma. “Cost-effective synthesis of aluminium oxide nanoparticles for environmental applications.”. *J. Envron. Manag.*, 207:412–418, 2018.
DOI: https://doi.org/10.1016/j.jes.2018.12.008.

[76] S. A. Hassanzadeh-Tabrizi and E. Taheri-Nassaj. “Economical synthesis of al$_2$o$_3$ nanopowder using a precipitation method.”. *Mat. Lett.*, 63(27):2274–2276, 2009.
DOI: https://doi.org/10.1016/j.matlet.2009.07.035.

[77] H. Kim, S. Yang, and J. Lee. “Energy-efficient synthesis of aluminium oxide nanoparticles using moderate heating.”. *Mat. Chem. Phy.*, 184:49–56, 2016.
DOI: https://doi.org/10.1016/j.matchemphys.2015.01.019.

[78] F. Sangor and M. A. Al-Ghouti. “Waste-to-value: synthesis of nano-aluminum oxide (nano-γ-al$_2$o$_3$) from waste aluminum foils for efficient adsorption of methylene blue dye.”. *Case Stud.Chem. Environ. Eng.*, 8:100394, 2023.
DOI: https://doi.org/10.1016/j.cscee.2023.100394.

[79] S. Banerjee, S. Dubey, R. K. Gautam, M. C. Chattopadhyaya, and Y. C. Sharma. “Adsorption characteristics of alumina nanoparticles for the removal of hazardous dye, orange g from aqueous solutions.”. *Arab. J. Chem.*, 12(8):5339–5354, 2019.
DOI: https://doi.org/10.1016/j.arabjc.2016.12.016.

[80] M. Y. Hussein, A. N. A. Al-naemi, and F. Y. Aljaberi. “Experimental study of produced water treatment using activated carbon with aluminum oxide nanoparticles, nanofiltration and reverse osmosis membranes.”. *J. Eco. Engg.*, 24(5):78–87, 2023. URL 10.12911/22998993/161231.

[81] E. K. Tsoutsa, A. K. Tolkou, I. A. Katsoyiannis, and G. Z. Kyzas. “Composite activated carbon modified with alcl$_3$ for the effective removal of reactive black 5 dye from wastewaters.”. *J. Comp.Sci.*, 7 (6):224, 2023.
DOI: https://doi.org/10.3390/jcs7060224.

[82] P. Seo, B. Bhadr, N. A Ahmed Khan, and S. H. Jhung. “Adsorptive removal of pharmaceuticals and personal care products from water with functionalized metal-organic frameworks: remarkable adsorbents with hydrogen-bonding abilities.”. *Sci. Rep.*, 6:34, 2016.
DOI: https://doi.org/10.1038/srep34462.

[83] F. F. D. Oliveira, K. O. Moura, L. S. Costa, C. B. Vidal, and A. R. Loiola. “Reactive adsorption of parabens on synthesized micro- and mesoporous silica from coal fly ash: ph Effect on the modification process.”. *ACS Omega*, 5(7):3346–3357, 2020.
DOI: https://doi.org/10.1021/acsomega.9b03537.

[84] P. Loganathan, S. Vigneswaran, and J. Kandasamy. “Enhanced removal of nitrate from water using an aluminium oxide-modified biochar.”. *J. of Envron. Manage.*, 131C:363–374, 2013.
DOI: https://doi.org/10.1016/j.jenvman.2013.09.034.

[85] H. Dai, H. Liu, Y. Chen, Y. Xie, H. Zou, and S. Wu. “Enhanced adsorption performance of al$_2$o$_3$ based composites by incorporating magnetic nanoparticles.”. *J. Colloid Interface Sci.*, 506:271–279, 2017.
DOI: https://doi.org/10.1016/j.jcis.2017.06.019.

[86] J. Zhao, J. Wang, M. Li, X. Liu, and Y. Yuan. “Fabrication of al$_2$o$_3$ coated diatomite composite for the adsorption of heavy metal ions.”. *Water Sci. Technol.*, 80(11):2141–2148, 2019.
DOI: https://doi.org/10.11648/j.ijec.20180201.13.

[87] S. Ali, A. Shafqat, A. Yasir, Z. Zareen, and I. S. Butler. “Synthesis of γ-alumina (al_2o_3) nanoparticles and their potential for use as an adsorbent in the removal of methylene blue dye from industrial wastewater.”. *Nanoscale Adv.*, 1(1):213–218, 2019.
DOI: https://doi.org/10.1039/C8NA00014J.

[88] V. K. Gupta, S. Agarwal, and T. A. Saleh. “Synthesis and characterization of alumina-coated carbon nanotubes and their application for lead removal.”. *J. Hazard. Mater.*, 185(1):17–23, 2011.
DOI: https://doi.org/10.1016/j.jhazmat.2010.08.053.

[89] X. Wang, X. Wang, Y. Liu, and Y. Fan. “Removal of cadmium from water by adsorption on nano γ- al_2o_3 particles.”. *Environ. Sci. Poll. Res.*, 26:5951–5959, 2019.
DOI: https://doi.org/10.1007/s11356-018-4040-8.