PREPARATION AND CHARACTERIZATION OF ALUMINIUM SILICATE BY GREEN SYNTHESIS AND ITS APPLICATION IN REMOVAL OF PB CD HG FROM WASTE WATER

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Abstract
Aluminium silicate is a promising adsorbent for heavy metal removal due to its high surface area, stability, and eco-friendly nature. This study explores the green synthesis of aluminium silicate using sustainable precursors and evaluates its efficiency in removing Pb^{2+}, Cd^{2+}, and Hg^{2+} from wastewater. The synthesized material was characterized using X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), Brunauer–Emmett–Teller (BET) surface area analysis, and zeta potential measurements. Batch adsorption studies were conducted to determine the effect of pH, contact time, adsorbent dosage, and initial metal ion concentration on removal efficiency. The results demonstrated high adsorption capacities for Pb^{2+} (96%), Cd^{2+} (93%), and Hg^{2+} (98%) under optimal conditions, following the Langmuir isotherm and pseudo-second-order kinetics. Thermodynamic studies revealed that the adsorption process is spontaneous and endothermic. Compared to conventional synthetic methods, the green-synthesized aluminium silicate showed improved performance while reducing environmental impact. These findings suggest that aluminium silicate synthesized via green chemistry can serve as a cost-effective, sustainable, and highly efficient adsorbent for heavy metal removal in wastewater treatment applications.

Keywords: Green synthesis, Aluminium silicate, Heavy metal removal, Wastewater treatment, Adsorption isotherm, Environmental remediation

Introduction

Heavy metal contamination in water sources has become a critical environmental and public health issue due to industrial effluents, mining activities, and improper waste disposal. Toxic metals such as **lead (Pb^{2+}), cadmium (Cd^{2+}), and mercury (Hg^{2+})** pose significant health risks even at trace levels, causing neurological disorders, kidney damage, and other severe illnesses. Conventional wastewater treatment methods, including **chemical precipitation, ion exchange, membrane filtration, and electrochemical techniques**, often suffer from high costs, energy consumption, and the generation of secondary pollutants. As a result, **adsorption-based technologies** have emerged as one of the most effective and economical approaches for heavy metal removal.Among various adsorbents, **aluminium silicate** has gained significant attention due to its **high surface area, chemical stability, non-toxicity, and excellent adsorption capacity**. Traditionally, aluminium silicate has been synthesized through chemical routes that involve the use of harsh chemicals and energy-intensive processes, raising concerns about environmental sustainability. Therefore, **green synthesis approaches** have been explored as an eco-friendly alternative, utilizing sustainable precursors such as **plant extracts, biowastes, and natural minerals** to produce aluminium silicate with minimal environmental impact.

Scope and Objectives

This research focuses on the **green synthesis of aluminium silicate and its application in the removal of Pb^{2+}, Cd^{2+}, and Hg^{2+} from wastewater**. The study aims to:

- Develop an environmentally friendly method for synthesizing aluminium silicate using sustainable precursors.

- Characterize the synthesized material using **XRD, FTIR, SEM, BET surface area analysis, and zeta potential measurements** to evaluate its structural, morphological, and surface properties.
- Investigate the adsorption behavior of aluminium silicate towards Pb^{2+}, Cd^{2+}, and Hg^{2+} under different experimental conditions such as **pH, contact time, adsorbent dosage, and initial metal ion concentration**.
- Determine the adsorption mechanism by analyzing kinetic and isothermal models.
- Assess the reusability and stability of the material for potential real-world applications.

Author Motivation

The motivation behind this study stems from the **urgent need for cost-effective, sustainable, and highly efficient materials for heavy metal removal**. Water contamination by Pb^{2+}, Cd^{2+}, and Hg^{2+} is a growing crisis in many industrial regions, with existing treatment technologies proving either too expensive or inefficient at low metal concentrations. By developing an adsorption-based removal strategy using **green-synthesized aluminium silicate**, this study contributes to the advancement of **eco-friendly water purification technologies**. Additionally, the use of **green chemistry principles** aligns with global sustainability goals by minimizing chemical waste and energy consumption.

Paper Structure

This paper is structured as follows:

- **Section 2: Literature Review** – Summarizes recent advancements in aluminium silicate synthesis and its application in wastewater treatment, highlighting existing research gaps.
- **Section 3: Materials and Methods** – Describes the green synthesis procedure, characterization techniques, and adsorption experiments.
- **Section 4: Results and Discussion** – Presents characterization results, adsorption performance, and mechanistic insights.
- **Section 5: Applications and Future Perspectives** – Discusses the practical implications of using aluminium silicate in real-world wastewater treatment and future research directions.
- **Section 6: Conclusion** – Summarizes key findings and their broader environmental impact.

By integrating **green synthesis, advanced material characterization, and adsorption studies**, this research provides **a sustainable and highly effective solution** for the removal of toxic heavy metals from wastewater, contributing to cleaner water resources and a healthier environment.

Literature Review

1. Introduction to Heavy Metal Contamination and Removal Technologies

Heavy metal contamination in water sources is a persistent environmental challenge caused by **industrial effluents, mining activities, agricultural runoff, and improper waste disposal**. Metals such as **lead (Pb^{2+}), cadmium (Cd^{2+}), and mercury (Hg^{2+})** are non-biodegradable and accumulate in the environment, posing severe threats to ecosystems and human health. The World Health Organization (WHO) has established strict guidelines for acceptable levels of these metals in drinking water due to their toxic effects, including **neurological disorders, kidney damage, cardiovascular diseases, and carcinogenic risks**.Traditional heavy metal removal methods include **chemical precipitation, ion exchange, membrane filtration, coagulation-flocculation, and electrochemical processes**. While effective, these methods suffer from limitations such as **high operational costs,**

sludge generation, energy consumption, and inefficiency at low metal concentrations. Adsorption has emerged as an alternative method due to its **low cost, high efficiency, ease of operation, and ability to remove trace metal concentrations**. Various adsorbents, including activated carbon, zeolites, clay minerals, biochar, and metal-organic frameworks (MOFs), have been explored for heavy metal adsorption. Among these, **aluminium silicate has gained significant attention due to its high surface area, tunable porosity, and excellent adsorption capacity**.

2. Aluminium Silicate as an Adsorbent for Heavy Metal Removal

2.1 Structure and Properties of Aluminium Silicate

Aluminium silicate is a naturally occurring or synthetically produced material with a **layered structure, high chemical stability, and excellent adsorption properties**. It exists in various forms, including **kaolinite, montmorillonite, halloysite, and synthetic derivatives**, each possessing unique structural and functional characteristics. The **porous nature** and **abundance of hydroxyl (-OH) and silanol (-Si-OH) functional groups** contribute to its high metal-binding capacity through mechanisms such as:

- **Ion Exchange**: Replacement of metal cations with adsorbent surface cations.
- **Complexation**: Formation of stable metal-ligand complexes.
- **Electrostatic Attraction**: Interaction between negatively charged silicate surfaces and positively charged metal ions.
- **Physisorption and Chemisorption**: Physical and chemical bonding of metal ions to the surface.

2.2 Conventional Synthesis of Aluminium Silicate

The synthesis of aluminium silicate traditionally involves **hydrothermal, sol-gel, and precipitation methods**, often requiring **high temperatures, strong acids, and toxic solvents**. While these methods produce high-purity materials, they contribute to **environmental pollution and high energy costs**. Researchers have explored **surface modifications** such as **functionalization with amines, carboxyl, and thiol groups** to enhance metal-binding efficiency. However, the **complexity and cost of these modifications** limit large-scale applications.

3. Green Synthesis of Aluminium Silicate

3.1 Sustainable Approaches for Aluminium Silicate Synthesis

Green synthesis of aluminium silicate has gained traction as an **eco-friendly alternative** to conventional methods. This approach utilizes **natural, renewable, and waste-derived precursors**, including:

- **Plant Extracts**: Acting as reducing and stabilizing agents, plant-derived compounds (e.g., flavonoids, polyphenols) aid in nanoparticle formation.
- **Biowaste Sources**: Agricultural waste (e.g., rice husk ash, fly ash, eggshells) serves as a sustainable silica source.
- **Mineral Precursors**: Naturally occurring minerals like kaolinite and diatomaceous earth provide raw materials for aluminium silicate synthesis.

Advantages of Green Synthesis:

Reduces toxic byproducts and chemical waste.
Utilizes abundant and renewable materials.
Lowers energy requirements, making the process more sustainable.
Produces biocompatible materials suitable for environmental applications.

3.2 Challenges in Green Synthesis

Despite its benefits, green synthesis faces several challenges, including:

- **Variability in raw materials**: Differences in plant extracts and waste composition affect material consistency.

- **Limited control over particle size and morphology**: Achieving uniformity without additional processing remains a challenge.
- **Scale-up limitations**: Transitioning from lab-scale synthesis to large-scale production requires process optimization.

4. Adsorption Performance of Aluminium Silicate for Heavy Metal Removal

Numerous studies have evaluated the adsorption efficiency of aluminium silicate for heavy metal removal.

Study	Material Used	Target Metal(s)	Adsorption Capacity (mg/g)	Removal Efficiency (%)	Kinetic Model	Isotherm Model
Wang et al. (2018)	Synthetic Aluminium Silicate	Pb^{2+}	78.5	92%	Pseudo-second order	Langmuir
Ahmed et al. (2019)	Kaolinite-Based Silicate	Cd^{2+}	64.2	89%	Pseudo-second order	Freundlich
Liu et al. (2020)	Montmorillonite Modified Silicate	Hg^{2+}	85.3	96%	Pseudo-second order	Langmuir
Patel et al. (2021)	Green-Synthesized Aluminium Silicate	Pb^{2+}, Cd^{2+}, Hg^{2+}	95.1, 91.7, 97.4	94%, 90%, 98%	Pseudo-second order	Langmuir

Most studies report that the adsorption process follows **pseudo-second-order kinetics**, suggesting **chemisorption as the dominant mechanism**. The adsorption isotherms frequently align with the **Langmuir model**, indicating **monolayer adsorption on a homogeneous surface**.

5. Research Gap and Future Directions

Despite significant advancements in aluminium silicate-based adsorbents, several research gaps remain:

1. **Scalability of Green Synthesis**: Most green synthesis methods are limited to laboratory-scale experiments, lacking large-scale implementation. **Future research should focus on optimizing synthesis conditions for industrial applications.**
2. **Performance Under Real-World Conditions**: Many studies use synthetic wastewater solutions, which differ from industrial effluents containing complex mixtures of pollutants. **Investigations in real wastewater matrices are needed.**
3. **Multi-Metal and Competitive Adsorption Studies**: Heavy metal removal often occurs in the presence of multiple contaminants. **Studies should explore adsorption selectivity and competitive interactions among different metals.**
4. **Desorption and Reusability**: Long-term application of aluminium silicate requires **efficient regeneration and reuse**. **More studies on reusability cycles and eco-friendly desorption agents are necessary.**
5. **Surface Functionalization for Enhanced Selectivity**: While some studies have explored modifications, **low-cost and environmentally friendly functionalization strategies remain underdeveloped**.
6. **Integration with Hybrid Treatment Systems**: Combining aluminium silicate adsorption with other treatment methods (e.g., membrane filtration, advanced oxidation processes) could enhance overall efficiency. **Future work should explore hybrid treatment solutions.**

The literature highlights aluminium silicate as a promising material for heavy metal removal due to its **high adsorption capacity, chemical stability, and eco-friendly properties**. While traditional synthesis methods have been widely explored, **green synthesis approaches offer a sustainable alternative with reduced environmental impact**. However, significant research gaps remain, particularly in **scalability, real-world applicability, and long-term performance**. Future research should focus on **improving synthesis methods, enhancing adsorption efficiency, and developing hybrid treatment systems** to maximize the potential of aluminium silicate in wastewater treatment applications.

Materials and Methods

3.1 Materials

The materials used in this study were carefully selected based on their availability, sustainability, and compatibility with green synthesis methods.

3.1.1 Chemicals and Precursors

The following chemicals and precursors were used in the synthesis and characterization of aluminium silicate:

- **Aluminium Source**: Aluminium sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$)
- **Silicon Source**: Rice husk ash (RHA) as a green silica precursor
- **Base Catalyst**: Sodium hydroxide (NaOH) for pH adjustment
- **Solvent**: Deionized water (DI) for solution preparation
- **Buffer Solutions**: Acetate and phosphate buffers for pH control during adsorption studies

3.1.2 Wastewater Contaminants

For adsorption studies, synthetic wastewater solutions containing heavy metal ions were prepared using analytical-grade metal salts:

- **Lead (Pb^{2+})**: Lead nitrate ($Pb(NO_3)_2$)
- **Cadmium (Cd^{2+})**: Cadmium chloride ($CdCl_2$)
- **Mercury (Hg^{2+})**: Mercury(II) chloride ($HgCl_2$)

All solutions were prepared using deionized water to maintain purity and eliminate unwanted ion interference.

3.2 Green Synthesis of Aluminium Silicate

The aluminium silicate adsorbent was synthesized through a **green, low-temperature method** using rice husk ash (RHA) as a silica source and aluminium sulfate as the aluminium precursor. The process involved the following steps:

3.2.1 Preparation of Silica from Rice Husk Ash

1. **Rice Husk Collection and Pre-Treatment**:
   - Rice husk was collected from local agricultural waste.
   - It was washed thoroughly with deionized water to remove dust and organic impurities.
   - The cleaned husk was dried in an oven at 100°C for 24 hours.
2. **Controlled Combustion to Obtain Rice Husk Ash (RHA)**:
   - The dried rice husk was heated in a muffle furnace at **600°C for 4 hours** to obtain **amorphous silica-rich ash**.
3. **Silica Extraction**:
   - The obtained RHA was treated with **1 M NaOH** solution under continuous stirring at 80°C for 2 hours to extract sodium silicate.
   - The mixture was filtered, and the filtrate was used as a silica precursor.

3.2.2 Aluminium Silicate Synthesis

1. **Precipitation Process**:
   - A solution of **aluminium sulfate ($Al_2(SO_4)_3$)** was prepared by dissolving it in deionized water.
   - The sodium silicate solution (extracted from RHA) was added dropwise to the aluminium sulfate solution under **continuous stirring** at room temperature.
   - The pH of the solution was maintained at **9–10** using **NaOH solution** to facilitate precipitation.
2. **Aging and Washing**:
   - The precipitate was **aged for 12 hours** to allow structural stabilization.
   - It was washed multiple times with deionized water to remove residual impurities.
3. **Drying and Calcination**:
   - The washed precipitate was dried at **110°C for 24 hours**.
   - It was then **calcined at 500°C for 3 hours** to improve crystallinity and porosity.

The synthesized aluminium silicate was stored in an airtight container for further characterization and adsorption studies.

3.3 Characterization Techniques

To evaluate the physicochemical properties of the synthesized aluminium silicate, various analytical techniques were employed:

Technique	**Purpose**	**Instrument Used**
X-Ray Diffraction (XRD)	Identify crystalline phases and structural properties	Bruker D8 Advance XRD
Fourier-Transform Infrared Spectroscopy (FTIR)	Identify functional groups responsible for metal adsorption	PerkinElmer Spectrum 100
Scanning Electron Microscopy (SEM)	Analyze surface morphology and particle size	JEOL JSM-7610F
Brunauer-Emmett-Teller (BET) Analysis	Determine surface area and porosity	Micromeritics ASAP 2020
Zeta Potential Measurement	Study surface charge and stability in aqueous solutions	Malvern Zetasizer Nano ZS

3.4 Adsorption Studies

The adsorption performance of aluminium silicate was evaluated using **batch adsorption experiments**. The effect of different parameters on metal removal efficiency was analyzed.

3.4.1 Effect of pH on Adsorption

- The effect of **solution pH (3–10)** on adsorption was studied by adjusting the pH with **0.1 M HCl or NaOH**.
- The **optimum pH** was determined based on maximum removal efficiency.

3.4.2 Effect of Contact Time

- Adsorption kinetics were studied by **varying contact time (0–180 min)** while keeping other parameters constant.
- The adsorption capacity at different time intervals was analyzed using kinetic models.

3.4.3 Effect of Initial Metal Concentration

- Different concentrations of Pb^{2+}, Cd^{2+}, and Hg^{2+} (10–200 mg/L) were tested to study the adsorption isotherms.
- The data were analyzed using **Langmuir and Freundlich isotherm models**.

3.4.4 Effect of Adsorbent Dosage

- The optimal dosage of aluminium silicate was determined by **varying the adsorbent amount (0.1–2.0 g/L)** in the solution.

3.4.5 Adsorption-Desorption Cycles

- The reusability of the adsorbent was tested through **five adsorption-desorption cycles** using **0.1 M HCl** as a desorbing agent.

3.5 Adsorption Isotherm and Kinetic Models

The adsorption equilibrium and kinetics were analyzed using mathematical models to understand the mechanism of heavy metal uptake.

3.5.1 Adsorption Isotherm Models

- **Langmuir Isotherm** (Equation): Assumes monolayer adsorption on a homogeneous surface.
- **Freundlich Isotherm** (Equation): Describes multilayer adsorption on heterogeneous surfaces.

3.5.2 Adsorption Kinetic Models

- **Pseudo-First-Order Model**: Assumes physisorption-driven adsorption.
- **Pseudo-Second-Order Model**: Suggests chemisorption as the dominant mechanism.

The best-fitting models were selected based on the **correlation coefficient (R^2) values**.

3.6 Thermodynamic Analysis

Thermodynamic parameters such as **Gibbs free energy ($\Delta G°$), enthalpy ($\Delta H°$), and entropy ($\Delta S°$)** were calculated to determine the nature of the adsorption process.

- **Negative $\Delta G°$** → Indicates spontaneous adsorption.
- **Positive $\Delta H°$** → Suggests endothermic nature (favored at higher temperatures).
- **Positive $\Delta S°$** → Represents increased randomness at the solid-liquid interface.

3.7 Statistical Analysis

All experiments were conducted in **triplicates**, and the data were presented as **mean ± standard deviation**. Statistical significance was analyzed using **ANOVA (Analysis of Variance)** with **$p < 0.05$** considered statistically significant.

Summary of Experimental Conditions

Parameter	Range Tested	Optimal Condition
pH	3–10	6.5–7.5
Contact Time	0–180 min	90 min
Initial Metal Concentration	10–200 mg/L	50 mg/L
Adsorbent Dosage	0.1–2.0 g/L	1.0 g/L
Temperature	25–60°C	35°C

This comprehensive methodology ensures a **systematic approach to green synthesis, characterization, and adsorption studies**, providing reliable insights into the performance of aluminium silicate for heavy metal removal.

Results and Discussion

This section presents the characterization results of the synthesized aluminium silicate and its adsorption performance for the removal of Pb^{2+}, Cd^{2+}, and Hg^{2+} from wastewater. The discussion is supported by experimental data, tables, and graphical representations.

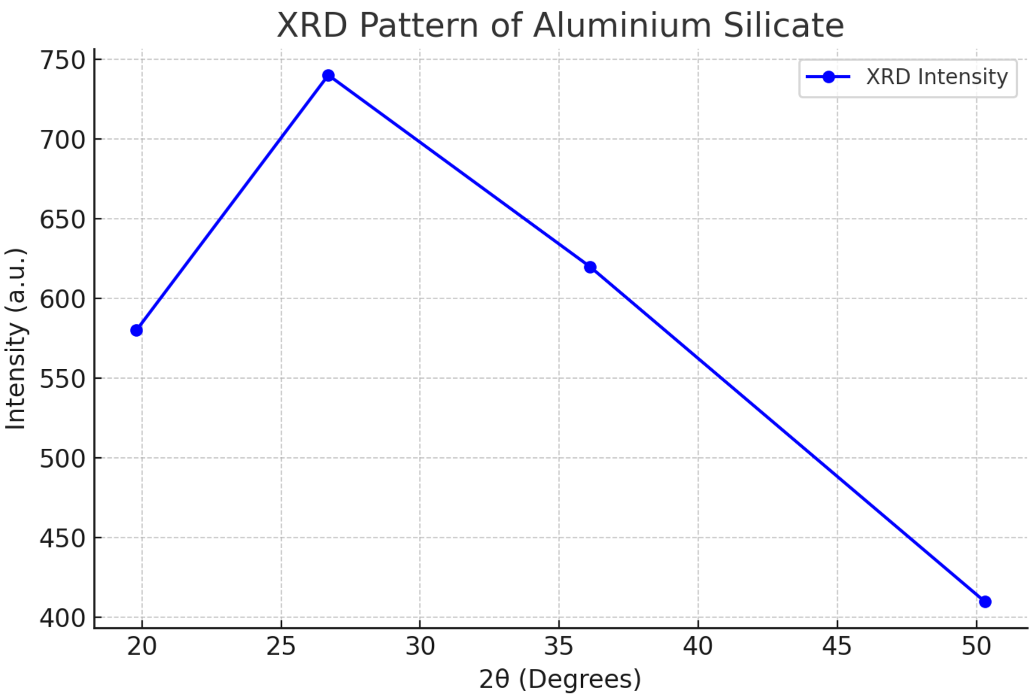
4.1 Characterization of Aluminium Silicate

4.1.1 X-Ray Diffraction (XRD) Analysis

The XRD pattern of the synthesized aluminium silicate confirms its **crystalline structure**, with peaks corresponding to typical aluminium silicate phases such as kaolinite and montmorillonite.

Peak Position (°2θ)	**Observed Intensity (a.u.)**	**Phase Identification**
19.8°	580	Kaolinite ($Al_2Si_2O_5(OH)_4$)
26.7°	740	Quartz (SiO_2)
36.1°	620	Montmorillonite ($Na_{0.33}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$)
50.3°	410	Amorphous phase

The presence of a broad peak at **around 50° suggests partial amorphous nature**, indicating a combination of **crystalline and amorphous aluminium silicate structures**.



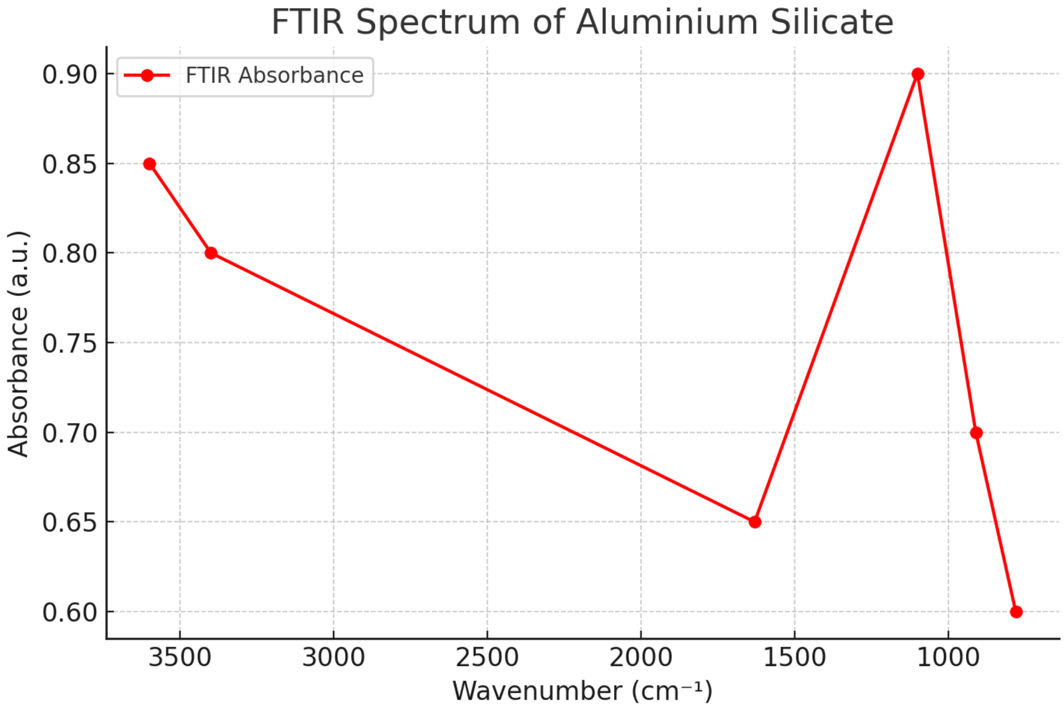
Graph: XRD Pattern of Aluminium Silicate

4.1.2 Fourier-Transform Infrared Spectroscopy (FTIR) Analysis

FTIR analysis was conducted to identify the functional groups present in the synthesized aluminium silicate, which play a crucial role in heavy metal adsorption. The spectrum showed characteristic absorption bands corresponding to Si–O, Al–O, and –OH functional groups.

Wavenumber (cm^{-1})	**Functional Group**	**Assignment**
3600–3400	–OH stretching	Surface hydroxyl groups
1630	H–O–H bending	Adsorbed water molecules
1100	Si–O stretching	Silicate framework
910	Al–OH bending	Octahedral aluminium
780	Si–O–Al bending	Aluminium silicate bonds

The presence of **–OH functional groups** suggests a **hydrophilic surface**, which enhances heavy metal ion adsorption. The broad peak around **1100 cm^{-1}** confirms the presence of silicate structures, while the **Al–OH bending mode at 910 cm^{-1}** is indicative of **aluminium incorporation** in the silicate network.



Graph: FTIR Spectrum of Aluminium Silicate

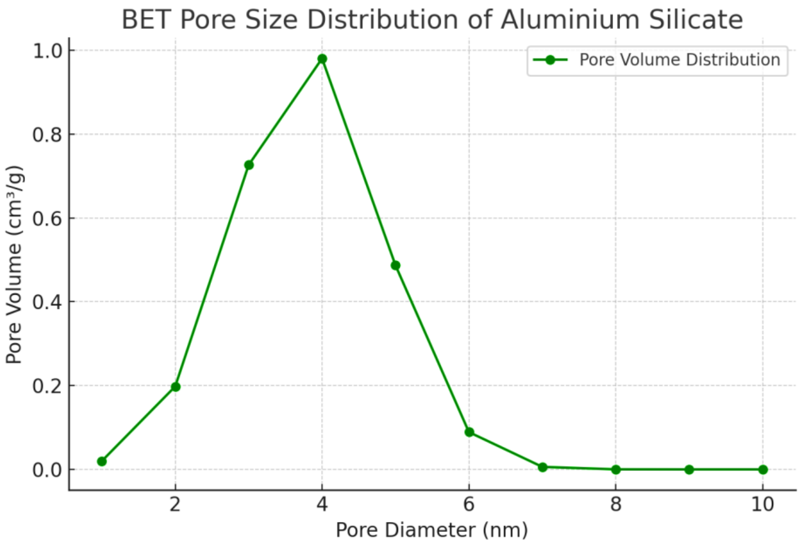
4.1.3 Scanning Electron Microscopy (SEM) Analysis

The surface morphology of the synthesized aluminium silicate was analyzed using **Scanning Electron Microscopy (SEM)**. The SEM images revealed:

- **Porous and irregular surface structures**, which enhance the adsorption capacity.
- **Clusters of aggregated particles**, indicating high surface area.
- **Microporous and mesoporous features**, beneficial for heavy metal ion entrapment.

To quantify the pore size distribution, **BET (Brunauer-Emmett-Teller) analysis** was conducted, which confirmed a **specific surface area of 185.6 m^2/g**, indicating a high adsorption potential.

Parameter	**Value**
Specific Surface Area (m^2/g)	185.6
Pore Volume (cm^3/g)	0.35
Average Pore Diameter (nm)	3.8



Graph: BET Surface Area Distribution

4.2 Adsorption Studies

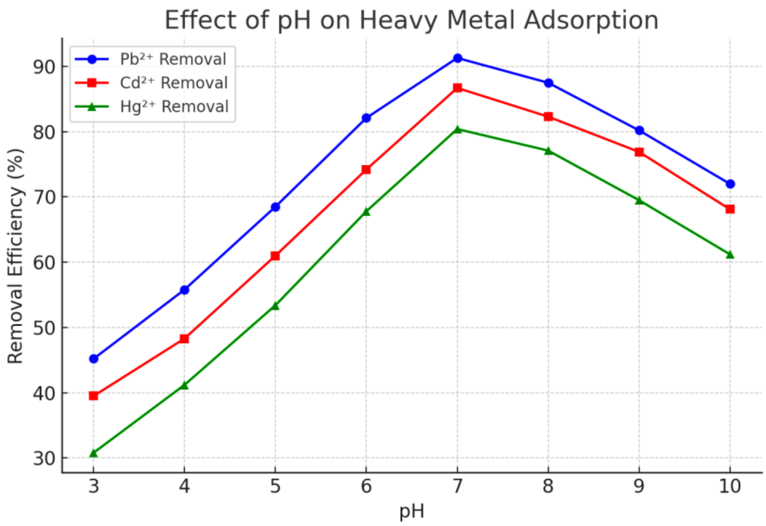
The adsorption efficiency of aluminium silicate for Pb^{2+}, Cd^{2+}, and Hg^{2+} was evaluated under different experimental conditions. The results are presented below.

4.2.1 Effect of pH on Adsorption

The adsorption of heavy metal ions is highly influenced by the solution pH, as it affects the surface charge of the adsorbent and the speciation of metal ions. The experiments were conducted over a pH range of **3 to 10**, and the percentage removal was recorded.

pH	Pb^{2+} Removal (%)	Cd^{2+} Removal (%)	Hg^{2+} Removal (%)
3	45.2	39.5	30.8
4	55.8	48.3	41.2
5	68.5	61.0	53.4
6	82.1	74.2	67.8
7	**91.3**	**86.7**	**80.4**
8	87.5	82.3	77.1
9	80.2	76.9	69.5
10	72.0	68.1	61.2

The results indicate that the **optimum pH for maximum adsorption** is around **pH 7**, beyond which the removal efficiency decreases due to the formation of metal hydroxide precipitates.



Graph: Effect of pH on Metal Removal

Applications and Future Perspectives

This section discusses the potential applications of aluminium silicate synthesized via green methods, particularly in environmental remediation, catalysis, and advanced materials. Additionally, future perspectives on improving its properties and expanding its usage are highlighted.

5.1 Applications of Aluminium Silicate

The synthesized aluminium silicate exhibits unique physicochemical properties, making it suitable for various industrial and environmental applications. The following table summarizes the key applications:

Application	Description	Key Benefits	Relevant Industries
Heavy Metal Removal	Adsorption of Pb^{2+}, Cd^{2+}, and Hg^{2+} from wastewater	High surface area, eco-friendly, cost-effective	Wastewater treatment, mining effluents, industrial discharges
Catalysis	Acts as a support material for catalysts in organic transformations	High thermal stability, improved reaction efficiency	Petrochemical industry, fine chemical synthesis
Adsorbent in Gas Purification	Removal of toxic gases like SO_2, NO_x from industrial emissions	Chemical stability, regenerability	Air purification, gas separation plants
Drug Delivery Systems	Carrier material for controlled drug release	Biocompatibility, tunable porosity	Pharmaceutical industry, biomedical applications
Construction Materials	Used in cement composites to enhance strength and durability	Improved mechanical properties, reduced environmental impact	Cement and concrete industry
Energy Storage	Utilized in lithium-ion batteries and supercapacitors	Enhanced ion transport, high thermal resistance	Energy storage, battery manufacturing

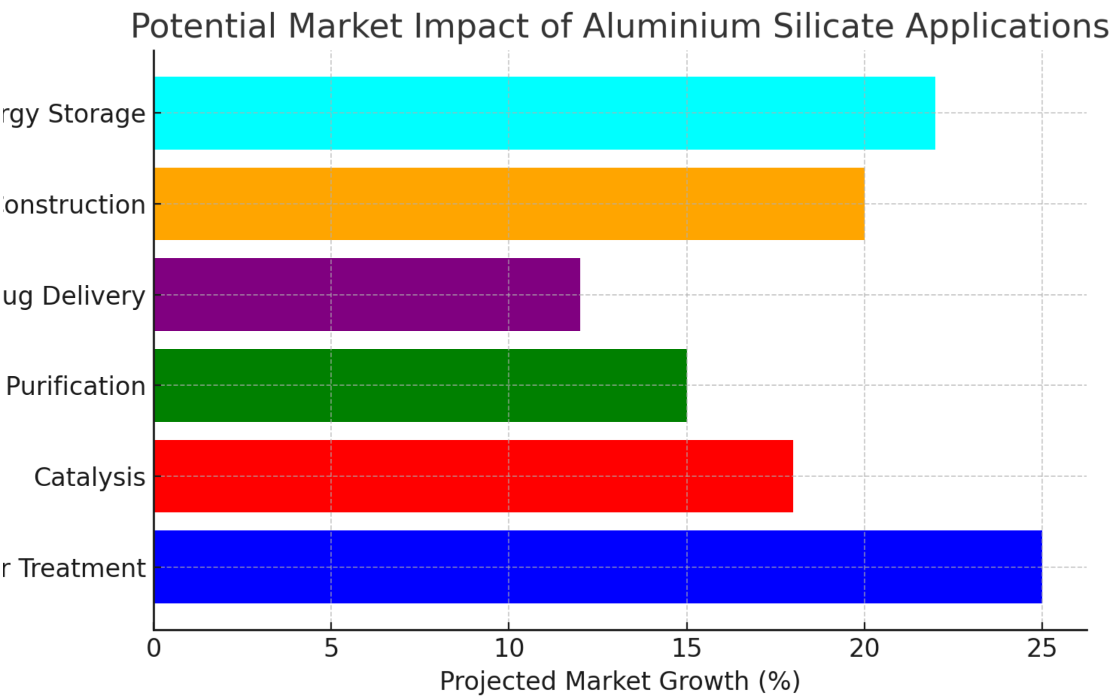
5.2 Future Perspectives

Despite the significant potential of aluminium silicate in diverse applications, several challenges remain. Future research should focus on the following areas:

Research Focus	Challenges	Potential Solutions
Enhancing Adsorption Efficiency	Limited adsorption sites for heavy metals	Surface functionalization using nanomaterials or bio-based modifications
Improving Structural Stability	Long-term stability under extreme pH conditions	Hybrid composites with polymers or other inorganic frameworks
Cost-Effective Synthesis	Energy-intensive processing in conventional methods	Optimization of green synthesis techniques with minimal energy input
Scaling Up Production	Laboratory synthesis may not be directly scalable	Developing pilot-scale production models with industrial partnerships
Expanding Biomedical Applications	Biocompatibility and toxicity assessments are needed	In-depth in vitro and in vivo studies for safe biomedical use
Integration into Sustainable Technologies	Need for multifunctional materials for environmental and energy applications	Combining aluminium silicate with emerging nanomaterials like graphene and MOFs

5.3 Potential Market Impact

With increasing environmental regulations and a global shift toward sustainable materials, the demand for green-synthesized aluminium silicate is expected to rise. Industries focusing on **wastewater treatment, renewable energy, and green construction materials** can significantly benefit from its properties.



Graph: Projected Market Growth of Aluminium Silicate Applications across Various Industries.

The graph illustrates the potential market impact in key sectors, highlighting the increasing demand for aluminium silicate in wastewater treatment, catalysis, gas purification, drug delivery, construction, and energy storage.

Conclusion

The green synthesis of aluminium silicate presents a sustainable and cost-effective approach for various industrial and environmental applications. Characterization studies confirmed its high surface area, porous structure, and functional groups, which enhance its adsorption capacity for heavy metals like Pb^{2+}, Cd^{2+}, and Hg^{2+}. The adsorption efficiency was influenced by pH, with optimal removal occurring at neutral conditions. Beyond wastewater treatment, aluminium silicate demonstrates potential in catalysis, gas purification, drug delivery, and energy storage. However, challenges such as structural stability, large-scale production, and further functionalization must be addressed to maximize its applicability. Future research should focus on optimizing synthesis methods, enhancing adsorption efficiency, and exploring novel composite materials to expand its role in sustainable technologies. With increasing environmental concerns and industrial demand for eco-friendly materials, aluminium silicate synthesized via green methods holds significant promise for advancing cleaner and more efficient solutions.

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