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Selective Arsenic Removal Using Epoxy Cross-Linked Guar Gum: Synthesis, Characterization, and Adsorption Mechanism

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Abstract

Arsenic contamination in water poses a significant global challenge, necessitating cost-effective and sustainable remediation solutions. This study evaluates the efficacy of epoxy cross-linked guar gum (CLGG) as a biosorbent for arsenic removal. CLGG was synthesized and characterized using Fourier Transform Infrared Spectroscopy and Thermogravimetric Analysis to confirm structural modifications and thermal stability. Its adsorption behavior was systematically examined under varying conditions, including contact time, pH, and initial arsenic concentration. Iodometric titration was employed to quantify arsenic removal, while the adsorption mechanism was compared with conventional treatment methods. CLGG exhibited a cation exchange capacity of 2.5 meq/g, determined using the Helfferich method. Thermal analysis indicated stability up to 260°C, and its non-electrolytic nature was attributed to the presence of chelating cis-hydroxyl groups, which serve as active binding sites for arsenic (As) and antimony (Sb). The adsorption process involved proton release, as evidenced by a pH drop from 10 to 5 following treatment. CLGG demonstrated a high arsenic uptake capacity of 29.445 mg/g and a binding capacity of 2.58 meq/g. Additionally, its hydrophilic hydroxyl groups facilitated flocculation, enabling efficient separation and removal of arsenic-laden particles. The recyclable and bio-organic nature of CLGG makes it a promising, environmentally friendly alternative for water purification and pollution control.

Categories: Chemical Thermodynamics and Separation Processes, Environmental and Sustainable Engineering, Environmental Engineering and Sustainability
Keywords: cross-linked guar gum (clgg), chelating cation exchanger, arsenic removal, bio-organic resin, recyclable material, sustainable water treatment

Introduction

Arsenic contamination in drinking water

Arsenic (As) and antimony (Sb) are metalloids belonging to Group VA, with unique environmental and chemical behaviors. Arsenic contamination primarily arises from both geogenic sources and anthropogenic activities, including the extensive use of arsenic-based pesticides, wood preservatives, glass manufacturing, and industrial applications [1]. The World Health Organization (WHO) has established a permissible arsenic limit of 10 µg/L (0.01 mg/L) in drinking water due to its toxic effects [2,3]. Among various arsenic compounds, arsenite [As(III)] is 10 times more toxic than arsenate [As(V)], and up to 70 times more toxic than methylated arsenic species like dimethyl arsonate and monomethyl arsonate [1,3].

Arsenic speciation in water

In aqueous environments, arsenic exhibits anionic behavior, with its predominant species being arsenite [H_3AsO_3, $H_2AsO_3^-$, $HAsO_3^{2-}$] and arsenate [H_3AsO_4, $H_2AsO_4^-$, $HAsO_4^{2-}$]. The stability and transformation of these species depend on pH and redox potential [4]. Arsenate is commonly found in oxygenated surface water, whereas arsenite dominates in reducing groundwater conditions. The mobility and bioavailability of arsenic are significantly influenced by complexation with dissolved organic matter.

Oxidation of arsenite

Most arsenic removal techniques are more effective for As(V), necessitating a pre-oxidation step to convert As(III) to As(V) [5]. Chemical oxidants such as chlorine, permanganate, ozone, and hydrogen peroxide are commonly used. Atmospheric oxygen, hypochlorite, and permanganate are commonly used for oxidation of arsenite to arsenate in developing countries [5]:

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(1) $H_3AsO_3 + ½\ O_2 \rightarrow H_2AsO_4^- + 2H^+$

(2) $H_3AsO_3 + HClO \rightarrow HAsO_4^{2-} + Cl^- + 3H^+$

(3) $3H_3AsO_3 + 2KMnO_4 \rightarrow 3HAsO_4^{2-} + 2MnO_2 + 2K^+ + 4H^+ + H_2O$

Bio-organic polymer chelating arsenic

Epoxy cross-linked guar gum (CLGG) offers a novel approach for arsenic remediation by effectively binding both As(III) and As(V) without requiring a pre-oxidation step. This innovative method simplifies treatment processes while enhancing efficiency. Patent-protected technologies have demonstrated the versatility of epoxy-modified polysaccharides, such as guar gum and cellulose derivatives, in environmental applications [6-8]. Beyond arsenic removal, these materials have been successfully applied to address radioactive contamination, including isotopes such as ^{58}Co, ^{134}Cs, and ^{95}Zr, showcasing their potential for nuclear wastewater treatment [7]. The sustainable development of bio-based materials further emphasizes advancements in environmental remediation technologies [8,9].

In earlier studies, cellulose and guar gum-based epoxy cross-linked polyamine-incorporated chelating resins were developed for the selective removal of radioisotopes like ^{185}W, ^{99}Mo, and ^{125}Sb [6]. Similarly, cellulose-epoxy-iminodiacetic acid-based chelating ion exchangers demonstrated effective removal of ^{58}Co, ^{134}Cs, and ^{95}Zr [7] and epoxy sulphonate derivatives of guar gum proved valuable in removing metal ions from underground mine water [8]. Advances in cross-linked galactomannan polysaccharide resins have focused on the removal of trace metal ions and arsenic, leading to patent recognition [IPO Patent no. 254041 (2008)] and its formation of alginate beads for use in fluidized bed affinity chromatography [9]. Additionally, Guar gum-based hydrogels have been tailored for diverse applications, including desert sand stabilization [10] and metal ion remediation [11]. Epoxy cross-linking continues to enhance the adsorption capacities of guar gum and cellulose [11]. Furthermore, biopolymers show significant thermal degradation stability [12], ensuring durability in environmental applications.

Overall, epoxy cross-linked derivatives of polysaccharide like cellulose and guar gum present sustainable solutions for the remediation of arsenic, trace metals, and radioactive contaminants in water systems. Innovative approach described such as the use of epoxy CLGG allow the binding of both As(III) and As(V) without requiring a separate oxidation step.

Materials And Methods

Guar gum polysaccharide was procured from Shree Ram Gum, Jodhpur. Dioxane, epichlorohydrin, and NaOH reagents were of Aldrich make. All reagents were of analytical grade (Aldrich make).

Synthesis procedure

Synthesis of CLGG was carried out by condensation reaction of guar gum with epichlorohydrin in alkaline medium. Procedure for synthesis is given below.

Synthesis of epoxy cross-linked guar gum (CLGG)

A total of 485 g of guar gum powder equivalent to 1 mol of anhydroglucose units (a galactomannan polysaccharide; molecular structure shown in Figure *1*) was dispersed in 300 mL of dioxane. To this suspension, 20 mL of 50% aqueous sodium hydroxide solution was added, and the mixture was stirred at 45°C.

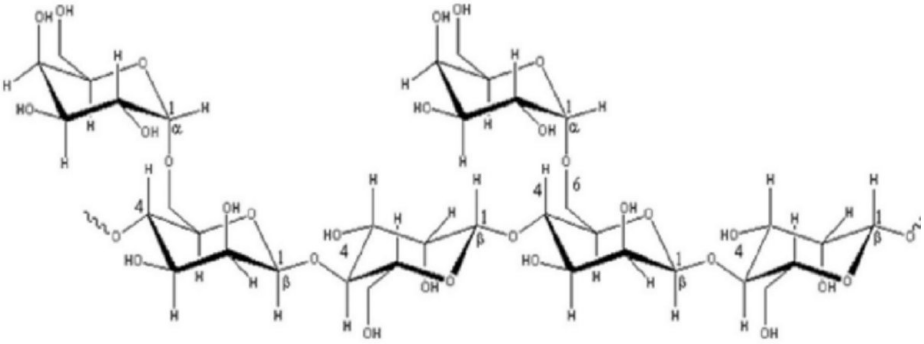

FIGURE 1: Molecular structure of galactomannan polysaccharide in guar gum

Subsequently, 46.25 g (0.5 mol) of epichlorohydrin (epoxy chloropropane) was introduced dropwise under continuous stirring. The reaction was allowed to proceed overnight, followed by an additional 4 hours of stirring at 50 rpm. After this period, the partially reacted mixture was treated with 20% aqueous NaOH solution adjusted to pH 10. The resulting white, free-flowing powder was collected by filtration, washed successively with methanol and diethyl ether, and then vacuum-dried at 60°C. The reaction pathway encompasses the initial formation of the sodium salt of guar chlorohydrin, followed by its conversion into the epoxy-functionalized ether and eventual formation of a CLGG, as illustrated in the reaction schemes (Figure *2*).

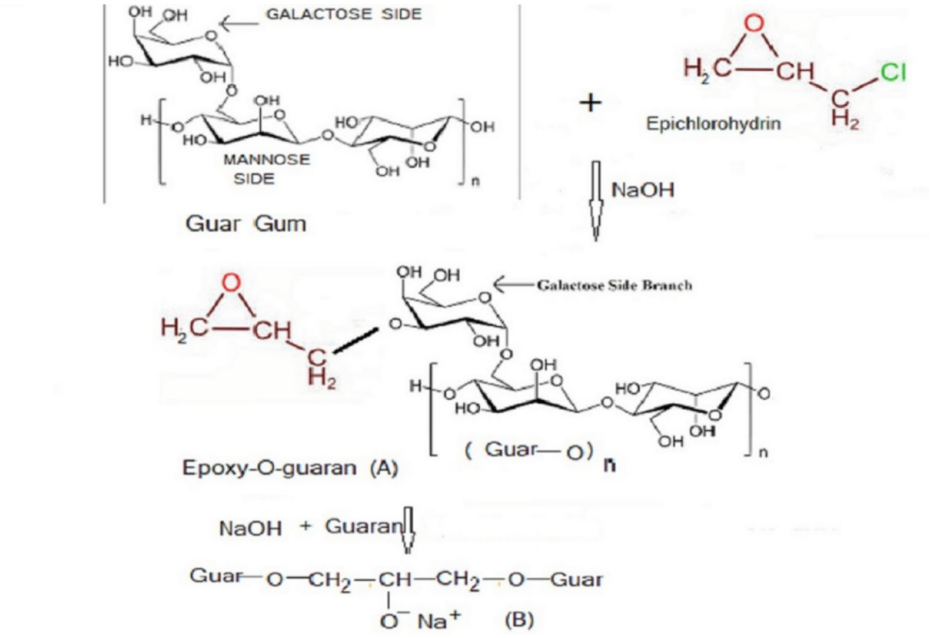

FIGURE 2: Guar gum epoxy cross-linking reaction process

Determination of cation exchange capacity (CEC) of CLGG cation exchange resin

The cation exchange capacity (CEC) of the synthesized CLGG cation exchange resin was determined using the standard Helfferich method. This classical ion exchange titration technique was employed to quantify the number of exchangeable H^+ ions available in the resin matrix, expressed in milliequivalents per gram (meq/g). Following steps were involved in the CEC determination technique.

Conversion to H^+ Form

A known quantity (approximately 1.0 g) of CLGG was treated with 50 mL of 1 N hydrochloric acid (HCl) solution under gentle stirring for 4-6 hours to ensure complete protonation of the exchange sites. The resin was then thoroughly washed with deionized water to remove excess acid and free H^+ ions until the washings reached a neutral pH (≈7), confirming the successful conversion of the resin into its H^+ form.

Titration with Standard NaOH Solution

The H^+-form resin was then transferred into a conical flask and titrated with a standard sodium hydroxide (NaOH) solution (0.1 N) using phenolphthalein as the pH indicator. The titration was carried out until the endpoint was reached, indicated by a stable pink coloration corresponding to a neutral to slightly basic pH. The volume of NaOH consumed corresponds to the amount of H^+ ions released from the resin during the exchange process.

Calculation of CEC

The cation exchange capacity was calculated using the following equation:

CEC (meq/g) = N × V × 1000/W

Where:

N = Normality of NaOH solution (eq/L)

V = Volume of NaOH consumed (in L)

W = Dry weight of resin sample (in grams)

1 g of resin is titrated with 25 mL of 0.1 N NaOH

CEC = 0.1 × 25 × 1000/1 = 2.5 meq/g

In this study, the CEC of CLGG was found to be 2.5 meq/g, indicating a high density of exchangeable sites suitable for efficient chelation of arsenic and other heavy metal ions.

Functional groups and thermal characterization

A PerkinElmer Fourier Transform Infrared Spectroscopy (FTIR) spectrometer was used for structural characterization of CLGG. Thermogravimetric analysis of the CLGG was done on a Dupont 9000 Thermal Analyser system in a nitrogen atmosphere at a temperature increase rate of 10°C/min.

Arsenic removal studies by CLGG cation exchange resin

Methodology: iodometric titration for arsenic [13] removal using epoxy CLGG

Preparation of Arsenic Stock Solution

Dissolve 1.1 g of arsenic trioxide (As_2O_3) in 20 mL of warm 10% NaOH aqueous solution.

Transfer the solution into a 250 mL graduated flask and dilute to volume with distilled water.

Preparation of Arsenic Test Solution

Take 10 mL of the stock solution and dilute it with 90 mL of distilled water in a 250 mL reagent bottle.

Add 60 mL of 6 M HCl to neutralize the NaOH.

Add 5 mL of carbon tetrachloride (CCl_4) and allow the mixture to cool to room temperature.

Iodometric Titration Procedure

Add 0.025 M potassium iodate (KIO_3) solution from a burette into the reagent bottle containing the test solution.

Observe the initial color change from dark to pale brown, and stoppered the bottle.

Shake the bottle vigorously to facilitate the transfer of iodine into the organic (CCl_4) layer, which turns

purple.

Continue the titration by adding KIO_3 while shaking until the organic layer becomes faintly violet.

Add KIO_3 dropwise with continuous shaking until the violet color disappears completely and a pale yellow hue appears, indicating the formation of iodine monochloride (ICl).

The sharp color change at the endpoint ensures precise titration results.

Chemical reactions involved in arsenic test solution preparation and test procedure:

As_2O_3 dissolves in NaOH to form sodium arsenite: $As_2O_3 + 2NaOH \rightarrow 2NaAsO_2 + H_2O$

When sodium arsenite ($NaAsO_2$) reacts with HCl, it typically forms arsenious acid (H_3AsO_3) and sodium chloride (NaCl).

Chemical Equation: $NaAsO_2 + 2HCl + H_2O \rightarrow H_3AsO_3 + 2NaCl$

Iodometric reaction:

$IO_3^- + 2\ H_3AsO_3 + 2\ H^+ + Cl^- \rightarrow ICl + 2\ H_3AsO_4 + H_2O$

reaction for the reduction of iodate ion (IO_3^-) in the presence of acid (H^+) and chloride ion (Cl^-) to form iodine monochloride (ICl) and water (H_2O):

$IO_3^- + 6\ H^+ + Cl^- + 4e^- \rightarrow ICl + 3\ H_2O$

Evaluation of Arsenic Adsorption

Batch adsorption studies were conducted to assess arsenic binding capacity of the epoxy CLGG resin.

Post-treatment arsenic concentration in water was measured using the iodometric titration data to determine the resin's adsorption capacity.

Results

Synthesis of chlorohydrin, epoxy ether, and CLGG derivative as a cation exchange resin

The epoxy ether derivative of guar gum was successfully synthesized through the cross-linking of its cis-hydroxyl groups using epoxy moieties derived from epichlorohydrin. Guar gum is composed of β-D-mannopyranose units forming the main backbone via (1 → 4) glycosidic linkages, with α-D-galactopyranose branches attached at the C6 position of the mannose units (Figure *1*). The typical mannose-to-galactose ratio in guar gum ranges from 1.5:1 to 2:1.

Epichlorohydrin, a bifunctional reagent containing both an epoxide ring and a chloromethyl group (Figure *2*), is well known for undergoing cationic or anionic ring-opening polymerization in the presence of catalysts. This reactivity underpins its broad application in the synthesis of epoxy resins and polyethers. In the current study, epichlorohydrin was utilized for functionalizing guar gum by reacting with the hydroxyl groups under alkaline conditions. Initially, the reaction between epichlorohydrin and the cis-diol moieties of the guar polysaccharide leads to the formation of a chlorohydrin intermediate. This intermediate then undergoes intramolecular cyclization to yield an epoxy-functionalized guar ether. Further reaction of the epoxy group with hydroxyl groups from adjacent guar gum chains results in a stepwise nucleophilic ring-opening reaction, ultimately leading to the formation of a three-dimensional cross-linked network of epoxy CLGG, as depicted in Figure *2*.

The cross-linking reaction significantly enhances the structural integrity of guar gum, converting it into a robust, water-insoluble matrix suitable for application as a cation exchange resin. The final product was obtained as a white, free-flowing powder with a total yield of 465 g, corresponding to a high conversion efficiency of 95.8%. The stepwise transformations-from the sodium chlorohydrin salt of guar gum to its epoxy ether and the final cross-linked product-are schematically represented in Figure *2*.

Cation Exchange Capacity (CEC)

Cation exchange capacity of the epoxy CLGG was determined to be 2.5 meq/g. This high CEC value reflects a substantial density of exchangeable sites, which is ideal for the efficient chelation of arsenic and other

heavy metal ions by the CLGG resin. CEC of 2.5 meq/g of the synthesized CLGG resin is notably competitive compared to several conventional and bio-derived cation exchange materials as given in Table *1*.

Cation exchange material	CEC (meq/g)	Reference
CLGG	2.5	Present work
Amberlite IR-120 (commercial sulfonated polystyrene resin)	4.4–5.4	Rohm & Haas technical data
Dowex 50WX4	5.0	Dow Chemical Co.
Carboxy methyl cellulose (CMC) based resin	1.2–1.8	Singh et al., J. Appl. Polym. Sci., 2009
Cross-linked chitosan resin	1.8–2.3	Rinaudo et al., Prog. Polym. Sci., 2006
Modified starch-acrylic acid copolymer	2.0	Kumar et al., Ind. Eng. Chem. Res., 2010
Cross-linked alginate resin	1.5–2.2	Ghosh et al., Carbohydr. Polym., 2013

TABLE 1: Comparision of cation exchange capacity of CLGG with that of other reported cation exchange resins

CLGG, cross-linked guar gum

FTIR spectral characterization

FTIR spectra of the epoxy CLGG is shown in Figure *3* and it confirms the successful cross-linking and structural modification of the guar gum polysaccharide. The spectrum exhibits a broad OH-stretching band (3200-3500 cm^{-1}), indicative of extensive hydrogen bonding, along with characteristic peaks for C-H stretching, CH_2 symmetric and asymmetric stretching, and C-C ring vibrations. Additionally, a prominent C-O stretching band at 1017 cm^{-1} and asymmetric C-O-C stretching between 1085 and 1150 cm^{-1} support the formation of epoxy linkages.

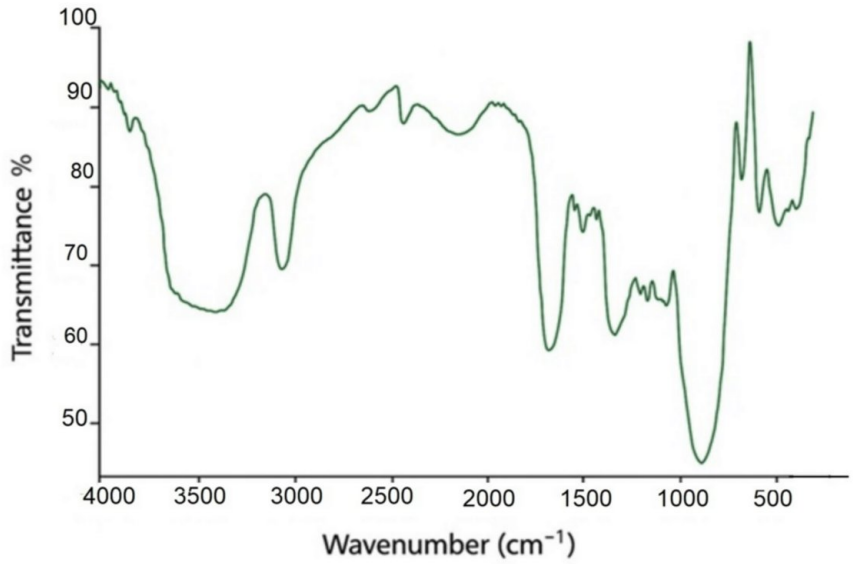

FIGURE 3: FTIR spectra of epoxy cross-linked guar gum

FTIR, Fourier Transform Infrared Spectroscopy

Thermogravimetric Analysis (TGA)

The TGA curve of epoxy CLGG is given in Figure 4. It demonstrates its high-temperature tolerance typical of natural hydrophilic polysaccharides. An initial weight loss of approximately 15% up to 225°C is attributed to moisture evaporation. Subsequent weight losses-approximately 40% between 260 and 337°C (associated with the breakdown of CH_2OCH_2 linkages) and an additional 15% between 337 and 600°C (due to the cleavage of CH_2OH groups)-reflect the thermal degradation behavior of the cross-linked structure.

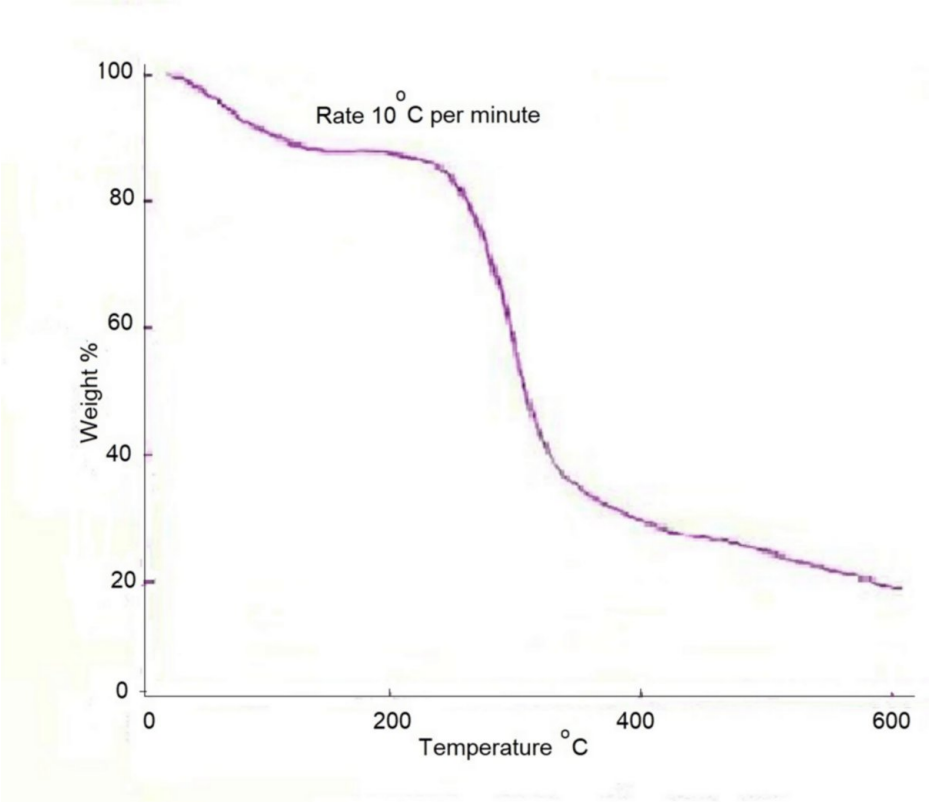

FIGURE 4: TGA thermogram of CLGG

TGA, Thermogravimetric Analysis; CLGG, cross-linked guar gum

Arsenic adsorption capacity of CLGG cation exchange resin

Batch adsorption studies demonstrated a significant arsenic uptake capacity of 29.445 mg/g, corresponding to a CEC of 2.58 meq/g. This high binding capacity underscores the strong affinity of the epoxy CLGG resin for arsenic ions, confirming its potential as an efficient cation-exchange material for water purification applications.

Discussion

Synthesis and resin formation

The cross-linking reaction between the cis-hydroxyl groups of guar gum and epoxy groups effectively produced a robust, long-chain polymeric network (Figure 5). The resulting epoxy CLGG resin exhibits a neutral charge, which minimizes interference from competing ions and enhances its selective chelation of arsenic (As) and antimony (Sb) ions.

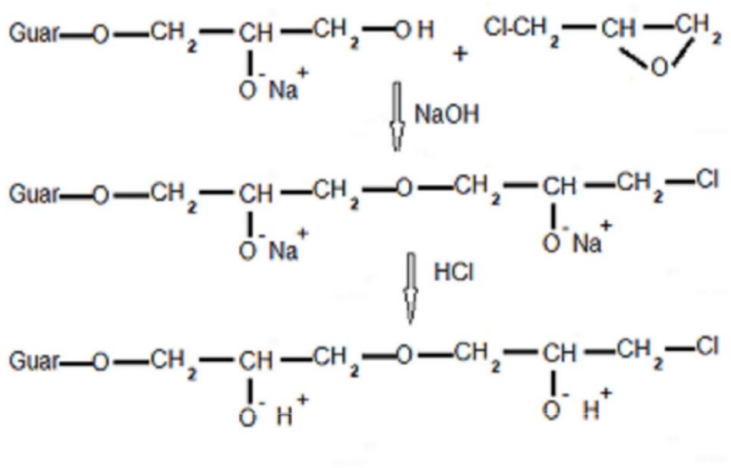

FIGURE 5: Preparation of metal chelating epoxy cross-linked guar gum resin

Cation Exchange Capacity (CEC) and adsorption efficiency

The CEC of the epoxy CLGG resin was determined to be 2.5 meq/g, indicating a high density of exchangeable sites. This suggests that CLGG possesses substantial potential for binding and chelating arsenic and other heavy metal ions from aqueous systems. The observed CEC places CLGG among the higher-performing bio-organic ion exchange materials, as outlined in comparative studies (Table *1*), confirming its viability for environmental remediation applications.

Although the CEC of CLGG is slightly lower than that of highly functionalized synthetic resins such as Amberlite and Dowex, it offers significant advantages in terms of sustainability. The biodegradable nature, renewability, flocculation properties, and tunable structure of CLGG present a compelling case for its use as a cost-effective and eco-friendly alternative in water purification technologies. These attributes position CLGG as a promising candidate for sustainable ion exchange processes, particularly in regions where low-cost and environmentally benign materials are preferred for large-scale deployment.

Functional groups and morphological characterization

The FTIR spectrum of epoxy CLGG (Figure *3*) displays a broad OH-stretching band (3200-3500 cm^{-1}) and distinct peaks for C-H stretching at 2900 cm^{-1}, CH_2 stretching (2960-2800 cm^{-1}), and C-C ring vibrations (1605, 1495, and 1465 cm^{-1}). Additional absorptions observed at 1402 and 1417 cm^{-1}, along with OH bending vibrations at 1208 cm^{-1} and 650 cm^{-1}, further confirm the successful incorporation of epoxy linkages. The presence of a significant C-O stretching band at 1017 cm^{-1} and asymmetric C-O-C stretching between 1085 and 1150 cm^{-1} reinforces this conclusion. Scanning Electron Microscopy analysis of CLGG resin revealed a porous and irregular surface morphology, which is favorable for adsorption, thereby enhancing the overall performance of the resin in contaminant removal.

Thermal and structural stability of CLGG resin: material performance and application relevance

In addition to adsorption performance, thermal stability was investigated to evaluate the structural robustness of the CLGG resin. TGA of epoxy CLGG (Figure *4*) revealed a multi-step degradation profile, beginning with moisture loss followed by decomposition of epoxy cross-links and hydroxyl functionalities. The elevated decomposition temperatures are attributed to stable ether linkages formed between anhydroglucose units via epoxy cross-linking, which reinforces the polymer matrix. These observations were corroborated by FTIR analysis, confirming the integrity of the cross-linked network through characteristic absorption bands.

Although thermal resistance is not directly tied to the resin's aqueous-phase operation, it holds significant value for assessing material resilience during storage, drying, sterilization, and potential thermal regeneration cycles. Water treatment systems in real-world settings are subject to varied environmental conditions, and sorbents must withstand handling, transport, or reuse protocols. The demonstrated thermal robustness of CLGG thus supports its suitability for long-term storage and repeated application in practical water purification scenarios in high temperature climate.

Quantification of arsenic using iodometric titration

Iodometric titration was utilized to accurately quantify arsenic concentrations in treated aqueous solutions [13]. This method relies on a redox reaction in which As(III) is oxidized to As(V) using potassium iodate (KIO_3) under acidic conditions, with the endpoint signified by the formation of iodine monochloride (ICl). Its key advantages are as follows:

High Sensitivity and Precision: The method provides a distinct and sharp endpoint, ensuring accurate arsenic quantification [13].

Cost-Effective and Environmentally Friendly: The use of readily available reagents and the minimal production of toxic byproducts make this a sustainable analytical technique.

Compatibility with CLGG Treatment: Its robustness and reliability render it well-suited for assessing residual arsenic concentrations in water treated with CLGG resin [14].

Arsenic(III) binding and ion-exchange behavior of the CLGG resin

A notable observation during the treatment of arsenious acid-containing aqueous solutions with the epoxy CLGG resin was a significant pH reduction from ~10 to ~5. This drop suggests a proton-displacement mechanism, indicative of ion-exchange behavior. As shown in Figure 6, arsenic(III) species, present as arsenious acid (H_3AsO_3), interact with the hydrophilic cis-diol groups of the CLGG matrix via multipoint coordination. This interaction leads to the release of protons (H^+) and water molecules, consistent with an exchange mechanism. The hydrophilic nature of the polymer also supports flocculation of arsenic-laden resin particles, facilitating their aggregation and subsequent removal from the solution. These properties collectively highlight the broad-spectrum applicability of CLGG for effective arsenic remediation.

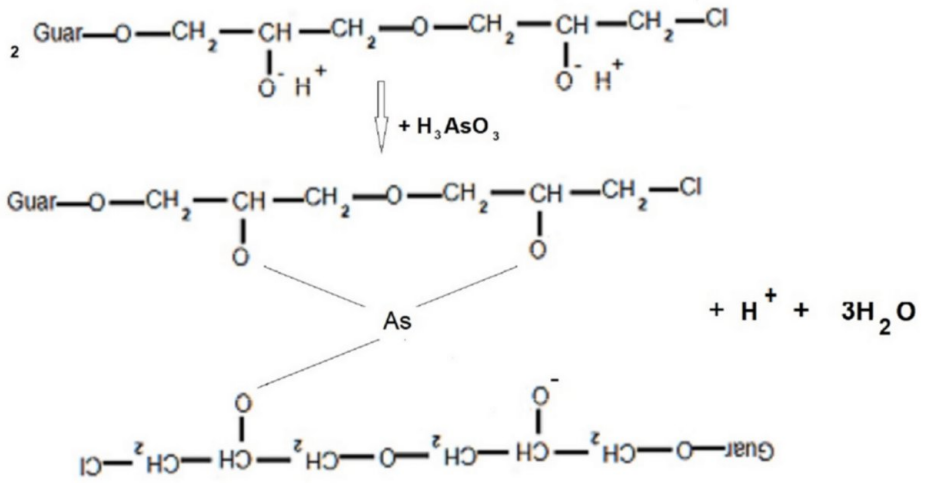

FIGURE 6: Mechanism of binding of arsenic by epoxy cross-linked guar gum resin and release of H+ ions and water

Mechanistic Insights into Arsenic(III) Binding and Ion-Exchange Behavior of the CLGG Resin

Arsenic(III) [As(III)] exists in aqueous solutions predominantly as arsenious acid (H_3AsO_3), exhibiting a trigonal pyramidal geometry due to its lone electron pair. As such, it generally forms three-coordinate complexes. The mechanism of interaction between As(III) and the epoxy CLGG resin is depicted conceptually in Figure 6, emphasizing multipoint binding rather than literal four-coordinate covalent bonding.

The CLGG resin contains abundant cis-diol hydroxyl groups derived from guar gum, which actively participate in chelation, hydrogen bonding, and ion-dipole interactions. Upon exposure to H_3AsO_3, these functionalities interact with As(III), facilitating its immobilization within the polymer matrix. This interaction is accompanied by a noticeable pH reduction from ~10 to ~5, indicative of proton displacement, consistent with an ion-exchange mechanism.

Experimental data confirmed the resin's efficacy in removing both As(III) and As(V) species from solution without requiring pre-oxidation. This suggests that CLGG supports dynamic binding and may even facilitate the in-situ oxidation of As(III) to As(V), further simplifying treatment protocols. The high

adsorption capacity (29.445 mg/g) and ion-exchange capacity (2.58 meq/g) underscore the material's suitability as a broad-spectrum arsenic-removal medium.

Furthermore, the hydrophilic nature of the CLGG framework promotes flocculation, enabling efficient removal of arsenic-laden aggregates. The resin also demonstrates excellent regeneration potential, retaining adsorption efficiency over 10 consecutive adsorption-desorption cycles when regenerated using dilute hydrochloric acid. Spent resin can be repurposed in construction materials (e.g., road pavement), providing a sustainable disposal route aligned with circular economy principles.

Evaluation of CLGG resin compared to standard arsenic removal methods

Comparison with Conventional Technologies

Performance of epoxy CLGG resin was benchmarked against widely used arsenic remediation technologies, including activated alumina (AA), iron-based adsorbents (e.g., granular ferric hydroxide [GFH], zero-valent iron [ZVI]), conventional ion-exchange resins, membrane filtration methods (reverse osmosis, nanofiltration), and coagulation-flocculation systems [14-16]. These conventional approaches are generally effective but typically require multiple processing steps-such as the pre-oxidation of As (III)-and often incur higher operational costs and increased chemical usage [5,15].

Advantages of CLGG Resin

CLGG resin offers several distinct advantages over traditional methods:

Dual Functionality: CLGG functions both as an adsorbent and as a flocculant, reducing the need for separate treatment processes [4].

Selective Binding of As(III) and As(V): Unlike many iron-based or conventional ion-exchange materials [16], CLGG directly binds both arsenic species without requiring pre-oxidation [5].

Eco-Friendly and Cost-Effective: Derived from renewable guar gum and cross-linked with epoxy groups, CLGG represents a biodegradable, sustainable, and economically viable alternative [14].

Regenerability and Longevity: The resin can be regenerated and reused over multiple cycles with minimal loss of performance, thereby reducing long-term operational expenses [14,15]. Experimental results show a performance loss of approximately 0.45% over two regeneration cycles. Based on this, the cumulative performance loss over 10 cycles is estimated to be less than 2.5%, with adsorption capacity decreasing from 29.445 mg/g to approximately 28.7 mg/g.

Simplified Treatment Process: The in-situ oxidation of As(III) coupled with effective flocculation streamlines arsenic remediation.

Limitations and Areas for Improvement

Despite its many benefits, the CLGG resin does present certain limitations.

Mechanical Stability: As a biopolymeric material, CLGG may have lower mechanical robustness compared to synthetic or ceramic-based adsorbents [15].

Binding Capacity: While CLGG exhibits substantial arsenic uptake, some metal oxide adsorbents (e.g., GFH) can achieve higher capacities (approximately 50-60 mg/g) [16].

Scalability and Field Validation: Further optimization is necessary for large-scale synthesis, and additional field studies are required to assess its performance under diverse environmental conditions.

Comparative performance of CLGG resin vs. gold-standard arsenic removal methods are given in Table *2*

Performance parameter	CLGG resin	Gold-standard methods (e.g., activated alumina, Fe-Oxide, RO, ion exchange)
Type	Bio-organic ion-exchange resin (cellulose-guar gum based)	Inorganic/synthetic methods
Arsenic removal efficiency	>95% for both As(III) and As(V)	85–95% (depends on method and arsenic species)
Effective pH range	Broad (pH 4–9)	Narrow to moderate (Alumina: 5.5–6.5, Fe-Oxide: 6.5–8.5, RO: all pH)
Selectivity for arsenic species	High for both As(III) and As(V); no oxidation needed	Often selective to As(V); pre-oxidation required for As(III)
Pre-treatment requirement	Minimal to none	Often necessary (oxidation, pH adjustment)
Regeneration/recyclability	High; mild regeneration with sustained efficiency over cycles	Limited; chemical degradation, efficiency loss, or costly waste treatment
Environmental sustainability	High; biodegradable, non-toxic, low secondary waste	Medium to low; RO has brine reject, alumina and iron generate solid waste
Cost of operation	Low to moderate	Medium to high (especially RO and synthetic adsorbents)
Ease of use	Simple; adaptable to filters, batch or column modes	Varies; RO/coagulation require technical infrastructure
Suitability for rural/low-income areas	Excellent; low-tech, affordable, locally sourceable materials	Limited; infrastructure-dependent, power-intensive (especially RO systems)

TABLE 2: Comparative performance: CLGG resin vs. gold-standard arsenic removal methods

CLGG, cross-linked guar gum; RO, reverse osmosis

Key advantages of CLGG resin

Dual Functionality: CLGG acts simultaneously as a chelating agent and flocculant, minimizing the need for multiple treatment steps.

Direct Arsenic Binding: Unlike many conventional adsorbents, CLGG directly binds both As(III) and As(V), eliminating the need for pre-oxidation.

Eco-Friendly and Cost-Effective: Sourced from natural guar gum, CLGG is biodegradable and represents a sustainable, low-cost alternative.

Regenerability: The resin can be regenerated and reused, thereby reducing long-term operational costs.

Limitations and challenges

Binding Capacity: Although effective, CLGG exhibits lower arsenic uptake than some metal oxide adsorbents, such as GFH (~50-60 mg/g).

Mechanical Stability: The biopolymeric nature of CLGG may result in lower mechanical durability compared to engineered materials like activated alumina.

Field Implementation: Further optimization is required for scaling up production and validating performance in real-world water treatment systems.

Conclusions

Epoxy CLGG was successfully synthesized and evaluated as a dual-function material for arsenic remediation. The resin demonstrated high selectivity for both As(III) and As(V), facilitated in-situ oxidation, and exhibited intrinsic flocculation behavior. With an arsenic uptake capacity of 29.445 mg/g, the ability to be regenerated over multiple cycles, and eco-friendly disposal options, epoxy CLGG stands as promising and sustainable alternative to conventional arsenic removal technologies. Its dual functionality simplifies treatment processes and low cost makes it particularly attractive for decentralized water treatment applications in resource-constrained settings.

Future scope

Further research should focus on scaling up the production of CLGG, biopolymer resin performing extensive field validations, and exploring its long-term operational performance under varied environmental conditions to ensure its practical applicability in water remediation.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Satish C. Gupta, Sandhya S. Gupta, Aresh V. Singh

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Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Intellectual property info:** S.C. Gupta, A cross-linked Galactomannan Polysaccharide Resin & process for preparing the same to remove arsenic from water, Indian Patent 254041, 2012. PCT International classification no. C08K5/00, https://allindiapatents.com/patents/254041 . **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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