

RESEARCH ARTICLE

Guar Gum: Superabsorbent Hydrogels for Dye Remediation

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Received: 2 October 2024 | **Revised:** 29 November 2024 | **Accepted:** 6 January 2025

Keywords: adsorbent | biopolymer | dye | hydrogel | waste

ABSTRACT

Hydrogels are 3-dimensional polymeric network structures that can absorb a large amount of water. The hydrogels possess remarkable hydrophilic characteristics, biocompatibility, and a high swelling ratio making them versatile in various applications. Guar gum biopolymer derived from guar beans showed hydrogel characteristics and can be modified by derivatization, copolymerization, crosslinking, and composite formation. Superabsorbent hydrogels made from guar gum have numerous applications across various industries such as agriculture for water retention in soil, drug delivery carriers, metal ion removal sorbents, dye adsorbents, environmental applications, and wastewater treatment. Dye plays an important role in water pollution. Various methods reported to remove dyes from waste water but among all the method adsorption is the best method. The use of guar gum-based superabsorbent hydrogels not only reduces waste but also promotes the development of ecofriendly and resource-efficient materials. This review mainly focuses on the properties of guar gum biopolymer, its modifications and its employability in various separation and enrichment techniques.

1 | Introduction

Water is a crucial component of all living organisms. The manufacturing industries as well as human activities consume tons of water in day-to-day life [1]. Freshwater resources are tarnished due to population expansion, industrial development [2], agricultural and domestic activities, and climate change. Due to global modernization water quantity and quality are decreasing significantly. Water pollutants such as heavy metal ions (mercury, copper, arsenic, lead, chromium, manganese, and cadmium [3]), microorganisms, oils (grease, pesticides), dyes [4] (azo, acid, basic, reactive, basic), and other inorganic and organic materials [5] caused the water pollution. Water pollution has detrimental effects on both the ecosystem and human health. The presence of pollutants in drinking water sources can lead to various problems such as gastrointestinal diseases, neurological disorders,

reproductive problems [6]. Various industries produce contaminated water that contains dyes such as the plastic industry, paper industry, textile industry [7], food industry [8], cosmetics industry, rubber industry, leather industry, detergents industry, and pharmaceuticals. Numerous methods are used for dye removals, such as adsorption [9], membrane separation, advanced oxidation, photocatalytic, membrane filtration, flocculation, and coagulation [10]. Industries utilize highly effective adsorption to decrease dangerous organic and inorganic dye material in wastewater treatment. The dye removal method depicts in Figure 1.

Among the various methods employed for dye removal adsorption is considered to be the most superior and effective approach. Adsorption is a process in which dye molecules attach to the surface of adsorbates like activated carbon, zeolites, silica

gel, activated alumina, and superabsorbent polymers (SAPs) [11]. The adsorption process is affected by factors such as pressure, temperature, and the nature of adsorbents and adsorbate. Adsorbent materials are preferred for treating wastewater owing to their porous structure and extensive surface area. The adsorption mechanism of dye is shown in Figure 2. There are two primary types of adsorption: physical (physisorption) and chemical adsorption (chemisorption). Physical adsorption is based on electrostatic interaction and weak van der Waal forces, while chemical adsorption involves the formation of strong chemical bond between adsorbent and adsorbate [12].

Superabsorbent polymers are well-known adsorbents having loosely crosslinked, 3-dimensional networks of flexible polymer. A water-absorbing hydrophilic polymer can absorb and hold enormous amounts of water compared to its mass [13]. SAPs can absorb water and fluids 300 times their dried weight. Superabsorbent materials are used in daily life such as disposable

diapers, drug delivery systems, water-blocking tapes, agriculture horticulture [14]. Biopolymers are organic substances that occur naturally. They have unique structural properties that are shaped by natural adaptation. Biopolymers such as collagen, cellulose, chitosan, chitin, lignin, guar gum (GG), alginate, starch are used as SAPs in various separation as well as enrichment applications. Zhao et al. [15] prepared a semi-IPN hydrogel composite through the photopolymerization of chitosan using ethylene glycol. The composite is effective for removing dyes such as acid red 18, methyl orange, acid orange 7, and basic violet. Zhou et al. [16] grafted cellulose with acrylic acid for the removal of methylene blue adsorption capacity of 2197 mg/g. Gomes et al. [17] synthesized a nanocomposite of starch-g-PAAc/CNWs the maximum dye removal was 90%. Ankit Verma et al. [18] used sodium alginate-cl-acrylic acid/graphite for the removal of methylene green adsorption of 91%. Among biopolymers, GG proved to be an excellent candidate owing to its high molecular weight, long molecular chain, nontoxicity, low cost,

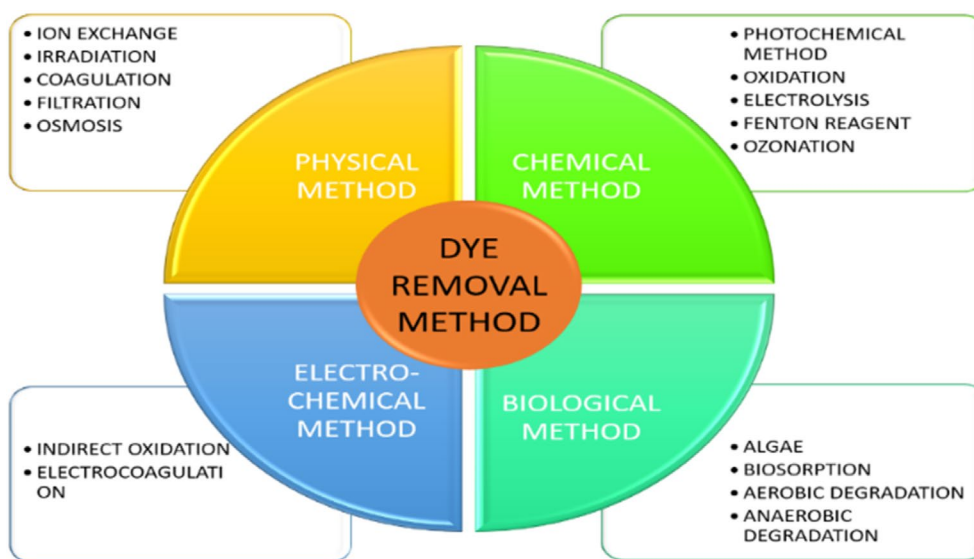


FIGURE 1 | Dye removal method.

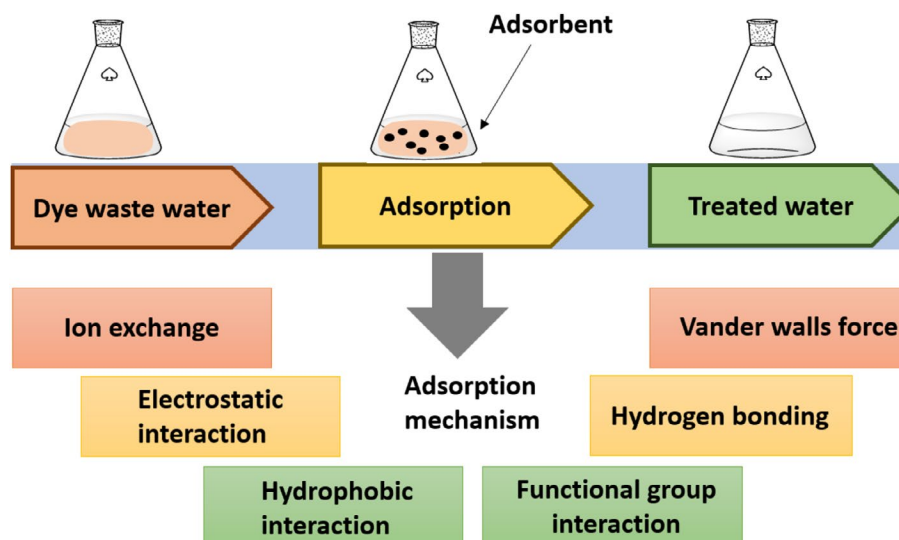


FIGURE 2 | Adsorption mechanism of dye.

biodegradability, biocompatibility, stability, as well as swelling properties.

2 | Guar Gum

GG is a naturally occurring substance derived from guar beans. Gawar, cuarine, cluster bean, and gaver are the other names of GG. The structure of GG is shown in Figure 3. India is responsible for producing 80% of the world's GG [2]. GG is a polysaccharide, composed of galactose and mannose units that are linked together by (1-6)- α -D-galactopyranose and (1-4)- β -D-galactopyranose linkage [19, 20]. GG is used in a wide range of industries including pharmaceutical, papermaking, cosmetics, textile, mining, water remediation, dyeing, control drug release, food, and petroleum industries. GG is a fine off-white powder that is tasteless, odorless, water-soluble and commonly used as a binding and thickening agent. GG has several unique properties including low toxicity, low cost, easy accessibility, eco-logical, water-soluble, biocompatibility, and biodegradability [21]. Exposure to intense heat may result in degradation and decreased functional efficiency. GG remains stable over a broad range of temperatures. It can dissolve in cold water, resulting in a highly viscous solution at low concentrations. The solubility of GG with water decreases in high ionic strength and it is pH-sensitive working effectively within a pH range between 4 and 10. In a solution, GG interacts with ions that crosslink with galactomannan chains, resulting in the formation of gels [22]. GG can stabilize the emulsion of oil in water by forming a shield around oil droplets. GG can also effectively combine with other ingredients such as protein, acids, salts, and sugar, which are often used in food formulation.

3 | Chemical Modification of GG

Although GG has many advantages, it faces certain challenges due to its poor mechanical and physical properties which significantly limit its uses. The GG's durability and performance tend to falter in harsh environments and require chemical modifications to deal with [23]. To overcome these limitations, researchers employed various modifications such as derivatization,

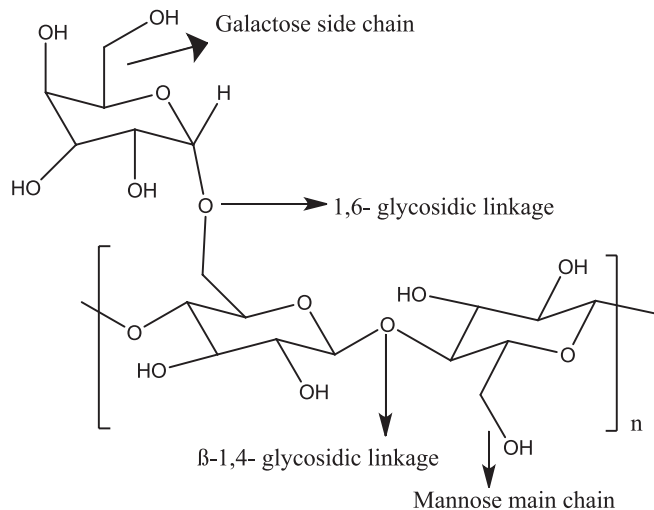


FIGURE 3 | Structure of guar gum.

copolymerization, crosslinking, composite formation. These modern approaches help to improve the applicability of GG across diverse fields. By modifying the raw GG favorable attributes were introduced preserving the fundamental properties of the biopolymer. For instance, carboxymethyl or hydroxypropyl derivatives can significantly enhance the solubility and solubilization time of GG solution exemplifying the remarkable potential of scientific innovation in optimizing natural polymers for multifaceted applications [24, 25]. Modification to the bare GG can be done by methods like crosslinking, derivatization, graft copolymerization, composite, s-IPNS, IPNS, and nanocomposites.

3.1 | Modification by Crosslinking

Crosslinking modifies GG by forming covalent bonds between polymer chains which results in improved properties as well as enhanced functionality as shown in Figure 4. Crosslinking enhances properties such as swelling ratio, viscosity, resistance to temperature, biocompatibility. Crosslinkers such as methylene bisacrylamide, divinyl benzene, epichlorohydrin, ethylene-glycol-dimethacrylate, glutaraldehyde (GA), ascorbic acid resulted in the interlinking of the polymeric chains together forming a closed-loop-like structure. Gliko-Kabir et al. [26] modified GG by crosslinking it with GA. The crosslinked GG showed high thermal stability as well as swelling capacity as compared to raw GG. Hongbo et al. [27] and co-workers worked on crosslinking GG using two different crosslinkers, phosphorus oxychloride and dialdehyde. The crosslinking and oxidation increase thermal stability and reduce the melting enthalpy. The GG crosslinked with a 56.2% aldehyde content showed the maximum adsorption capacity (Q_{max}) of 21.9mg/g for amino acid L-asparagine. Thombare et al. [28] in 2017 crosslinked GG with borax. The hydrogel was used for dye removal from the wastewater exhibiting 94% dye removal efficiency for methyl red and Aniline blue. Sharma et al. used pectin-crosslinked-GG/superparamagnetic iron oxide nanocomposite using ammonium persulfate, pectin, methylene bisacrylamide, ferrous chloride, and ferric chloride for the removal of the orthochlorophenol and meta-cresol. The maximum adsorption of orthochlorophenol and meta-cresol was found at 176.1 and 75.6mg/g, respectively [29]. Table 1 shows the GG crosslinked hydrogels and their usage in numerous industrial applications.

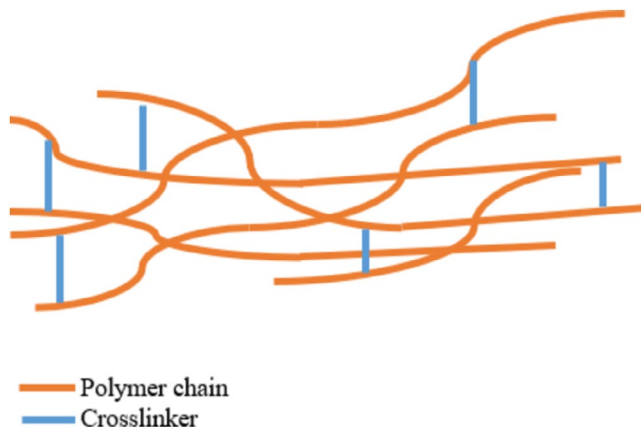


FIGURE 4 | Crosslinked hydrogels.

3.2 | Modification by Derivatization

GG can be derivatized by esterification, hydroxymethylation, carboxymethylation, sulfation, methylation, hydroxypropylation, methacryloylation, hydroxypropylation, O-2-hydroxy-3-trimethylammonia propylation, O-carboxymethyl-O-hydroxypropylation, and acryloyloxylation. Prabhanjan et al. [39] studied derivatization of GG with O-(2-hydroxyethyl), O-carboxymethyl, and O-(2-hydroxypropyl), and their effects were studied through alkaline degradations. The GG viscosity, rate of hydration, and solubility were affected by the alkaline degradation. At 4% and 8% alkali concentrations and 34°C temperature, there is initial minimum degradation, which increases with time and reaches a peak within 3 h. At a temperature of 70°C, viscosity rapidly declines within the first hour, leading to a watery solution. This highlights the crucial role of alkali in the kinetics of derivative degradation. Pasha et al. [40] derivatized GG by sodium-carboxymethyl hydroxypropyl which resulted in increased viscosity and hydration shown in Figure 5. The derivative had a 10.4% w/w sodium content and its degree of substitution was found to be 1.5. GG shows optimum hydration at pH 6, while the derivative shows optimum hydration at pH 7. He et al. [41] derivatized GG by using

ethylene glycol to irreversibly alkylate pure GG in the presence of an alkaline catalyst, hydroxyethyl GG has been developed. The hydroxyethyl GG is chemically and thermally stable in solutions and exhibits improved solubility toward alcohols. Kono et al. [42] prepared hydroxypropyl GG. A gel was produced by crosslinking hydroxypropyl GG with ethylene glycol diglycidyl ether. The viscoelastic properties of the gels varied with the degree of crosslinking. The gels exhibited excellent absorption properties and remained unaffected by changes in the pH or ionic strength of the solution. HPG gels are versatile gelation agents that find applications across various industrial sectors. Table 2 presents the GG derivatives and their utilization in various industrial applications.

3.3 | Modification by Graft Copolymerization

Graft copolymerization leads to an increase in the side branching and introduction of new functional groups to the backbone, hence enhancing the properties for certain specified applications. Soppimath et al. [47] grafted GG with polyacrylamide using the ceric ammonium nitrate as a free radical initiator. The authors investigated the hydrolysis of

TABLE 1 | Crosslinked hydrogels and their application.

Sr. no.	Hydrogels	Crosslinker used	Application	Ref.
1	Crosslinked-guar gum	Epichlorohydrin	Improved alkali and acid resistance, retrogradation, and viscosity stability	[30]
2	Crosslinked GG	Glutaraldehyde	Higher water swelling capacity in an acidic medium (pH 3)	[31]
3	Phosphate-crosslinked-GG	Trisodium trimetaphosphate	Removal of methylene blue dye	[32]
4	GG-crosslinked-PDA	Epichlorohydrin	Removal of mercury metal ion	[33]
5	CGG-crosslinked-Ascorbic acid	Ascorbic acid	Phosphorous-contaminated water treatment	[34]
6	GA-crosslinked-microspheres	Glutaraldehyde	Colon-specific drug delivery of methotrexate (MTX)	[35]
7	GG-crosslinked-soya lecithin	N, N'-methylene bisacrylamide	Removal of thiophanate methyl fungicide	[36]
8	Epi-crosslinked-alginate-guar gum	Epichlorohydrin	Lysozyme adsorption from egg white	[37]
9	GG-crosslinked-GA	Glutaraldehyde	Food, drug delivery, and biomedical	[38]

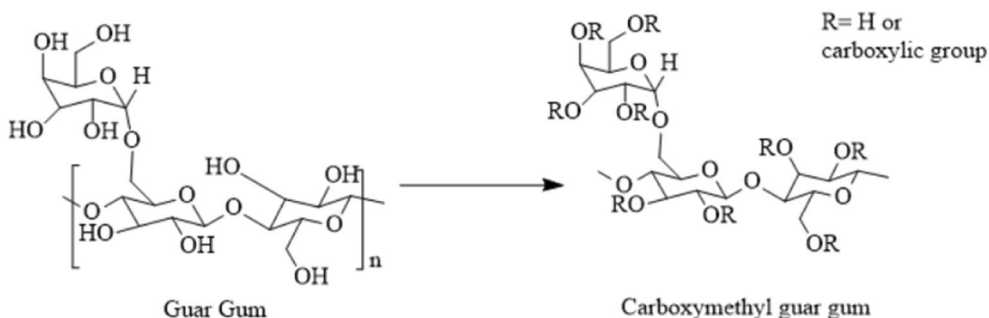


FIGURE 5 | Guar gum derivatives, carboxymethyl guar gum.

GG-g-poly (Aam) with 1 M NaOH at 60°C to get anionic microgels employed as pH-sensitive drug delivery systems shown in Figure 6. In 2011, Yan et al. [48] covalently grafted GG onto multiwall carbon nanotubes (MWCNTs). The weight of the grafted compound was about 21.6 wt% of the GG component which improved the GG-MWCNT dispersion in an aqueous solution and served as a model for the formation of iron oxide nanoparticles. GG-MWCNT-Fe₃O₄ showed superparamagnetism and good adsorption for dyes. The maximum adsorption of the GG-MWCNT-Fe₃O₄ for methylene blue and neutral red reached 61.92 and 89.85 mg/g. Similarly, Raval et al. [49] conducted grafting copolymerization of monomer 10 g of MMA (methyl methacrylate) onto 2 g of GG with initiator hydrogen

peroxide 5.0 × 10⁻³ M. The percentage add-on decreased with an increase in H₂O₂ (5 × 10⁻³ M) concentration suggesting that the rate of MMA homopolymerization was increased. The highest grafting percentage was at 61.50%. Table 3 shows the GG grafted copolymer and its use in various industrial applications.

3.4 | Modification by Composite Formation

GG composite formation involves combining GG with a cross-linker, modifiers, fibers to form a hybrid material to enhance its properties. This process includes shaping, compounding, and

TABLE 2 | Guar gum derivatives and their application.

Sr. no.	Guar gum derivative	Enhancement properties	Application	Ref.
1	Carboxymethyl GG	Protect the protein from low pH conditions and delivery	Gastrointestinal drug delivery of bovine serum albumin	[43]
2	Hydroxypropyl GG	High thermal stability, high viscosity	Petroleum industry as methanol/water fracturing fluids	[44]
3	Carboxylmethyl GG	Higher thermal stability, control rate of hydration	Removal of malachite green dye	[2]
4	Sulfated GG	Antioxidant and anti-inflammatory	Cancer chemopreventive	[45]
5	Methyl carboxymethyl GG	High thermal stability, high viscosity	Enhanced oil recovery	[44]
6	Partially carboxymethylated GG	Flexibility	Drug release Metronidazole in the colon	[23]
7	Sulfated GG	Antioxidant activity, metal chelating ability, scavenger of superoxide	Higher is the degree substitution than high antioxidant activity	[46]

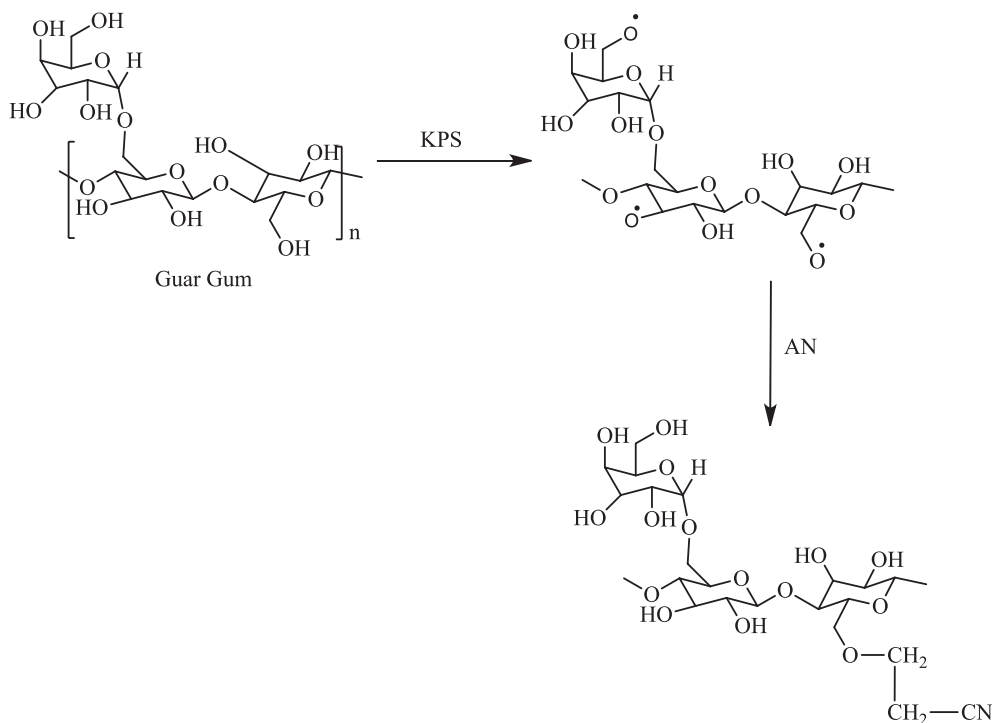


FIGURE 6 | Guar gum grafted copolymers of GG-g-PAN.

TABLE 3 | Guar gum grafted copolymers and their application.

Sr. no.	Grafted copolymer	Monomer	Initiator	Application	Ref.
1	GG-g-PAN	Acrylonitrile	Cerium ammonium nitrate	Higher swelling	[50]
2	Grafting polystyrene from guar gum	Styrene	Cuprous chloride, Penthamethyl-diethylenetriamine	Higher thermal stability	[51]
3	Grafted guar gum	Vinyl-2-pyrrolidone	Potassium persulfate	Protein partitioning of BSA, LO, and phytase	[52]
4	Guar gum grafted Polyacrylonitrile	Acrylonitrile	Potassium persulfate	Higher flame resistance	[53]
5	Guar gum grafted acrylic acid	Acrylic acid	Potassium peroxymonosulfate	Higher thermal stability	[54]
6	Guar gum grafted acrylic acid	acrylic acid	Ammonium persulfate	Dye removal of methylene blue	[1]
7	GG-g-methyl methacrylate	Methyl methacrylate	Cerium ammonium nitrate	Higher swelling	[55]
8	Guar gum polyacrylic acid	Acrylic acid	Ammonium persulfate	Dye removal of methylene blue	[56]
9	Guar gum Polyacrylamide	Acrylamide	Potassium bromate/ thiourea dioxide	Removal of chromium ion	[57]
10	Guar gum-g-poly(acrylate)	Acrylate	Persulfate-Tetramethylenediamine redox system	Against phytopathogenic fungus, <i>Pythium aphanidermatum</i>	[58]
11	GG-g-acrylamide	Acrylamide	Ammonium persulfate	Acid red 8 dye removal	[59]
12	Polyacrylamide-g- GG	Acrylamide	Cerium ammonium nitrate	Diltiazem hydrochloride and Nifedipine drug delivery	[60]
13	GG-g-poly (VP)	N-vinyl-2-pyrrolidone	Potassium persulfate	Sorption of Fe and Cr ions	[61]

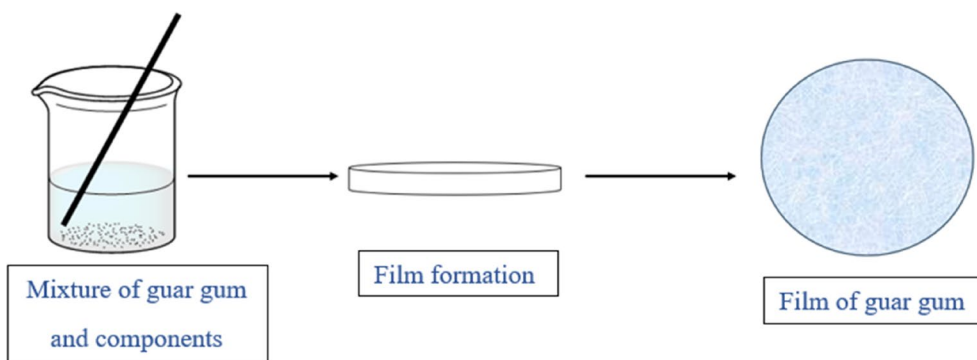


FIGURE 7 | Guar gum composite formation of films.

curing to achieve the desired composite structure. GG-based films are flexible, thin sheets made of GG. Banegas et al. [62] synthesized GG-based film crosslinked with 1-ethyl-3-(3-dimethyl-aminopropyl) carbodiimide hydrochloride (EDC). When EDC concentration was increased, water vapor absorption and swelling behavior decreased. The polymer structure and the hydrogen bond formation were impacted by the EDC content (10%–30%) which decreased the system's thermal stability. It

has applications in drug delivery and cell adhesion. Saurabh et al. [63] made GG based on nanocomposite films. Films containing closite 20A (10% wt/wt GG) and nano 116 (2.5% wt/wt GG) showed a 102% and 41% higher tensile strength, respectively. This increased the mechanical and barrier qualities of the nanocomposites compared to the control. Jussen et al. 2019 [64] made a film by drying GG hydrogels shown in Figure 7. They conducted tensile testing on the films that had a moisture

content ranging from 15% to 18% on a wet basis. The film's tensile strength was initially increased as the GG content was increased after a certain point it decreased. This decrease was attributed to the presence of air bubbles trapped within the films. The tensile strength ranged from 25 to 40MPa, comparable to cellophane and polyethylene's tensile strength data. Table 4 presents the GG composite and its use in numerous industrial applications.

3.5 | Modification of GG as s-IPNS

Semi-interpenetrating polymer networks (IPNs) refer to a type of polymer structure where another polymer network partially or fully interpenetrates one polymer network. In an s-IPN, one of the polymer networks is synthesized and formed first after which another polymer network is formed within or around it. Li et al. in 2006 [71] GG-poly (acrylic acid) s-IPN are formed with an initiator N, N, N', N'-tetramethyl ethylene and ammonium peroxy disulfate and crosslinked with methylene bisacrylamide. The swelling ratios of the s-IPN increased as the temperature of the swelling medium increased and the maximum at pH 7.52 with lower ratios below its pKa. Ghosh et al. [72] synthesized s-IPNS by carboxymethyl GG (CMGG) and crosslinked it with GA, gelatin, and monochloroacetic acid (monomer). This s-IPNS was used in drug delivery, molecules of biomedical importance, and sorbents for biotoxins. Shengfang Li et al. [73] prepared s-IPNs of GG crosslinked with N, N'-methylene bisacrylamide, Potassium persulphate as an initiator, methacrylic acid as a monomer, and sodium bisulfite. 5-aminosalicylic acid (5-ASA) was used for the colon-specific drug delivery. 5-ASA was entrapped with entrapment efficiency constantly exceeding 85%. In the hydrogen-bonded structure in the pH 2.2 medium, the hydrogel exhibits a

minimal release of 5-ASA. In a pH 7.4 medium, the release of the 5-ASA trapped in hydrogels can be accelerated by cecal bacteria enzymatic hydrogel degradation. Table 5 presents the modification of GG as s-IPNs for use in industrial applications.

3.6 | Modification of GG as IPNs

Conventional IPNs involve fully interwoven polymer networks, while semi-IPNs only involve one fully formed network before introducing the second network. Li et al. [78] prepared IPNs using GG crosslinked with N, N'-methylene bisacrylamide and GA. Increasing the GG content from 0% to 50%, decreased the gel's weight from 43.5 to 20g/L. The conversion rate initially increased and then decreased with increased GG content. The IPNs were used as controlled drug delivery systems that specifically targeted colonic drug release. Singha et al. synthesized [79]

TABLE 5 | Guar gum s-IPNs and their application.

Sr. no.	s-IPNs	Uses	Ref.
1	Guar gum-chitosan s-IPNs	Control release of cefadroxil drug	[74]
2	GG/HPAm/NaMMT s-IPNs	Synthetic oil reservoir water	[75]
3	PUNG s-IPNs	Improve in thermal stability	[76]
4	CH/GG-g-acrylamide s-IPNs	Control release of 5-fluorouracil drug	[77]

TABLE 4 | Guar gum composites and their application.

Sr. no.	Composite	Properties	Application	Ref.
1	GG/ chitosan films	Good tensile, better mechanical properties, lower oxygen permeability, puncture strength	Antimicrobial activity against <i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	[65]
2	GG, tara gum and locust bean gum film	Higher elastic modulus, good tensile strength, and good mechanical properties	Food packaging	[66]
3	Chitosan/GG/nanocrystalline cellulose nanocomposite films	Improved tensile strength, mechanical properties, highly transparent, reduced air permeability	Good tensile strength	[67]
4	Phosphate crosslinking GG film	Oil incorporation, mechanical strength, increased film hydrophobicity, and enhanced water barrier properties	Controlled release of volatile essential oil	[68]
5	GG-GC-MS Films	Good tensile and better mechanical properties	Antimicrobial activity against <i>Salmonella typhimurium</i> , <i>Bacillus cereus</i> , <i>E. coli</i>	[69]
6	GG films	Mechanical, physiochemical, and barrier	Improved mechanical properties	[70]

GGAAAMAPA by using N, N'-methylene bisacrylamide, acrylic acid (AA), acrylamide (AM), and 3-acryl amido propanoic acid (APA) as monomers using potassium persulfate and sodium bisulfite as a redox pair of initiators. GGAAAMAPA was used to remove dyes like methylene blue (MB), safranin (SF), and metal ions such as Cu(II), Pb(II), and Cd(II) from the aqueous solution. The highest adsorption for MB, SF, Cu(II), Pb(II), and Cd(II) was 27.06, 39.35, 41.98, 39.42, and 40.55, respectively. Kaith et al. [80] firstly synthesized Ggum-cl-poly (AA) s-IPNs with AA as a monomer, ammonium persulfate as an initiator, and hexamine as a crosslinker. Using an aniline monomer, these s-IPNs were then converted to IPNs (Ggum-cl-poly (AA-ipn-ANI)). The antibacterial properties, soil behavior, and biodegradation of the semi-IPN and IPNs were studied. The maximum weight loss due to biodegradation in the soil burial method was 70.06% for Ggum-cl-poly (AA) and 78.14% for Ggum-cl-poly (AA-ipn-ANI). Table 6 presents the modification of GG as IPNs for utilization in biomedical and industrial applications.

3.7 | GG-Based Nanocomposite

Nanocomposites are advanced materials that display improved thermal and mechanical properties. Nanocomposites [87] have emerged as a suitable alternative for addressing the limitations of microcomposites. Recently, there has been a remarkable rise in the utilization of GG-based nanocomposites. Orsu et al. [88] synthesized a CMGG nanocomposite scaffold ester film by crosslinking carboxymethyl GG (CMGG) with citric acid. They

found that the film with CMGG 0.3% w/v and citric acid 0.1% w/v had the best drug loading capacity and higher swelling index. They added ciprofloxacin, an antibiotic medication, to the film, resulting in wound healing within 5 days. Khan et al. 2020 synthesized [89] a composite material GG/GI/Ag-N-composite (GG/gelatin/silver nanocomposite) using different concentrations of AgNO₃. The investigations showed that GG/GI/Ag-N-3 showed the highest antibacterial activity against *Pseudomonas aeruginosa* (15 mm), *Escherichia coli* (14.5 mm), and *Staphylococcus aureus* (14.5 mm). Pathania et al. [90] prepared a nanocomposite of GG/AO (GG/Al₂O₃) using the ambient sol-gel method. The nanocomposites were employed in adsorption/photocatalysis reaction showing 80%–90% photodegradation of malachite green dye. Table 7 shows the modification of GG as nanocomposites for the various industrial applications.

4 | Application of GG

GG is widely used in various industries such as pharmaceuticals, papermaking, cosmetics, textiles, mining, petroleum refining [96]. GG can form viscous dispersions or gels in water due to its high swelling capacity. In the pharmaceutical industry, it acts as both a binding agent and a disintegrant, enhancing the cohesion of medication in tablet formulation. GG has several advantages such as being resistant to dissociation in the acidic environment of the stomach having the ability to form a gel-like substance that reduces the release of the drug and being resistant to microbial and enzymatic degradation in

TABLE 6 | Guar gum IPNs and their application.

Sr. no.	IPNs	Application	Ref.
1	CMGG-CS IPNs NPs	Controlled release alloxan of the antidiabetic drug	[81]
2	PAAm-g-GG IPNs	Controlled release of Ciprofloxacin drug	[82]
3	GG-g-PDMAEMA IPNs	Control release of 5-Fluorouracil for tumor-targeting delivery	[83]
4	CS/GG IPNs	Control release of isoniazid drug	[84]
5	Guar gum PU/PAN IPNs	Improve in mechanical properties	[85]
6	GG/Gg IPNs	Self-healing, intelligent wearable devices, human motion monitoring	[86]

TABLE 7 | Guar gum nanocomposite and their application.

Sr. no.	Nanocomposite	Application	Ref.
1	Chitosan/GG/nanocrystalline cellulose nanocomposite films	Improved tensile strength and reduced air permeability	[67]
2	GG-g-PNaA/REC	Improved tensile strength	[91]
3	GG-ZVI nanocomposite	Removal of methyl orange dye and ciprofloxacin	[92]
4	GG-multiwalled carbon nanotubes nanocomposite	Self-healing gel, coating, electronics, transportation	[93]
5	GG-MWCNT	Methylene blue and natural red dye removal	[48]
6	GG/ZnO	Removal of chromium (VI) metal ions	[94]
7	GG-g-poly (methyl methacrylate) nanocomposite	Horticulture, oil spill cleaning, removal of dye, and Agriculture	[95]

the large intestine. GG and its application in environmental remediation shown in Figure 8. GG has proven highly effective in various environmental remediation applications, particularly in wastewater treatment. It is widely used to create hydrogels and composites that can adsorb dyes, heavy metals, and other pollutants. GG-based materials can achieve improved adsorption efficiency and mechanical properties by incorporating additives such as nanoparticles or crosslinking agents. These materials have also shown promise in soil remediation, where they help stabilize contaminants and prevent erosion. In the case of oil spill cleanup, GG formulations assist in dispersing and thickening hydrocarbons, which facilitates biodegradation. Its versatility and ecofriendly nature make it a valuable tool for sustainable environmental management.

In the textile industry, GG provides film formation and thickening properties, which enhance product performance. It reduces the breaking of the yarns during sizing and gives good strength to fibers. GG has binding properties that make it useful for binding with dyes and other substances. In the food industry, GG is extensively utilized because it improves viscosity, reduced evaporation rate, moisture retention, amendment in freezing point, high water retention capability, gel formation, among other functions such as in cake, jelly, wine, bread, ice cream, yogurt, biscuits, tomato ketchup, etc. The concentration of GG varies in different food items like 0.5% in bread, 2% in yogurt, 0.15% in cake, 0.5% in ice cream, 0.5%–1% in sausage, and many more. The maximum use of GG in food is less than 2% [97]. It improves the yield of the dough in baked products by reducing the dough's unnecessary moisture content and fat adsorption. It contributes to thickening dairy products like yogurt, milk, cheese, etc. It maintains the texture of ice cream and beverages used for calorie-reducing and viscosity-controlling agents. In the cosmetics industry, GG is commonly used to prevent emulsion breakdown and maintain stability. GG improves the dispersion of the pigments, prevents water loss, improves emulsion stability, prevents phase separation and provides uniform coverage for creams, serums, lotions,

lipsticks, etc. [98]. It is used in toothpaste and shaving cream as a stabilizing agent to ensure a smooth texture and easy application. In the petroleum refining industry, the GG plays a crucial role as a viscosifier in hydraulic fracturing commonly known as fracking. When added to water-based fracturing fluids, GG increases their viscosity, which helps in the efficient transportation of proppant into the fractures created in the rock formation.

4.1 | Application in Dye Removal

Removal of the toxic industry effluents from industrial wastewater is needed of the day. Many methods were employed for the purpose and the adsorption promised to be most economic, efficient and reliable. A literature survey revealed that GG-based materials proved to be efficient adsorbents. Thombare et al. [28] cross-linked GG with borax to prepare hydrogels which was used as an adsorbent to remove aniline blue dye. The hydrogels showed 94% adsorption efficiency. Yan et al. [48] used GG-MWCNT-Fe₃O₄ for the removal of neutral red and MB dyes. The adsorption capacity for the removal of natural red and MB was 61.92 and 89.85 mg g⁻¹, respectively. Karadag et al. in 2020 [99] used P (propenamide/2-acrylamido-2-methyl-1-propane-sulfonic acid/GG) s-IPNs, and P (propenamide/2-acrylamido-2-methyl-1-propane-sulfonic acid/clinoptilolite/GG) biohybrid hydrogels for the removal of basic violet-1 dye. The dye removal percentage of the hydrogel was found to be 92.10%–96.25% (Table 8).

5 | Conclusion

In this article, the authors explored the efficiency of GG-based superabsorbent hydrogels as a sustainable approach for dye removal from wastewater. GG a naturally occurring polysaccharide, offers advantages such as biobased, nontoxic, biocompatible, biodegradability and responsiveness to environmental stimuli. These properties make it a suitable candidate for developing advanced hydrogels. The intrinsic chemical structure of GG, with its abundance of hydroxyl groups, facilitates chemical modifications and blending with other materials, such as metal oxides, carbon nanomaterials, or clays. This functionalization enhances its adsorption capabilities, mechanical strength, and overall stability, addressing the limitations of unmodified GG in wastewater treatment applications. Recent studies have shown that GG-based hydrogels can effectively adsorb various dye molecules, including both anionic and cationic dyes, owing to their high swelling capacity and the availability of active adsorption sites. Comparisons with conventional synthetic hydrogels highlight the superior environmental compatibility and lower cost of GG-based systems. However, challenges such as reduced performance in the presence of multiple contaminants and limited reusability under harsh conditions have been noted in the literature. Future research should focus on optimizing the structural properties of these hydrogels through the incorporation of nanomaterials or by employing advanced crosslinking techniques. Additionally, integrating these hydrogels with emerging technologies like nanofiltration, membrane bioreactors, and photocatalysis could further enhance their dye adsorption efficiency, offering innovative pathways for sustainable wastewater treatment solutions.



FIGURE 8 | Guar gum and its application in environmental remediation.

TABLE 8 | Guar gum polymer and dye removed.

Sr. no.	Modified guar gum polymer	Dye removal	Dye conc.	Time (min)	Ref.
1	Guar gum/activated carbon nanocomposite	Congo red	831.82 mg/g	240	[100]
2	Guar gum/silica nanocomposite	Reactive Blue 4, Congo red	579.01 mg/g, 233.24 mg/g	40 30	[101]
3	Guar gum/bentonite nanocomposite	Crystal violet	85%	300	[102]
4	TiO ₂ /guar gum hydrogel	Methylene blue	198.61 mg/g	300	[103]
5	Guar gum-crosslinked-poly (AA-ipn-aniline) IPN	Methylene blue	85.68%	240	[104]
6	GG-PAAm hydrogels	Crystal violet	85%	1200	[105]
7	Guar gum and silica nanocomposite	Reactive Blue, Congo red	99.68% 99.74%		[106]
8	Hydrazine-grafted guar gum	Rhodamine B, Methylene blue, Methyl Orange, Bromophenol Blue	1359.96 mg/g 1522.2 mg/g 868.83 mg/g 904.7 mg/g	30 30 30 30	[107]
9	GG-g-PAM crosslinked with borax	Brilliant Blue-19	80%	300	[108]
10	AgNPs/GG/Poly (AA) Nanocomposite	Methylene blue	833.33 mg/g	120	[1]
11	CMC/GG/GO nanocomposite	Malachite green	88.2%	60	[2]
12	GG/NiWO ₄ nanocomposite	Crystal violet, Phloxine B	220.21 mg/g 170.42 mg/g	50 40	[109]
13	Guar gum-cerium tungstate nanocomposite	Methylene blue	120 mg/g	120	[110]
14	Crosslinked magnetic layered double hydroxide/ GG Bio-nanocomposites	Methylene blue	84%	120	[111]
15	GG-grafted Terpolymer hydrogels IPNs	Methyl Violet	53.28 mg/g	600	[112]
16	Fe ^o @ GG-crosslinked-soya lecithin nanocomposite	Methyl Violet	81%	120	[113]
17	CMC/GG/CuO nanocomposite	Malachite green	92.4%	90	[114]
18	GG- crosslinked-Borax Composite	Methylene blue	99%	40	[115]
19	GG-Alg-Ag nanocomposite	Methylene blue	92.33%	120	[116]
20	Ag NPs@ MIL-100 (Fe)/GG	Methylene blue	99.10%	100	[117]
21	Chitosan-GG-silver nanocomposite	Rhodamine-6G, Reactive blue-21, Reactive red-141	95%	15	[118]
22	Starch/poly (AA-cl-AAm)/Fe/Zn nanocomposite hydrogel	Malachite green, fast green	91% 82%	300	[119]
23	GG-g-poly (HEMA)	Bismarck brown Y	97.58%	1440	[120]
24	GG-g-4HPAN	Congo red, methylene blue	81% 94.31%	360 360	[121]

6 | Future Research Work

Future research on GG-based superabsorbent hydrogels should focus on enhancing their effectiveness in dye remediation. Innovative chemical modifications, such as grafting with advanced functional groups or blending with nanomaterials, could improve their adsorption efficiency and mechanical properties. It is also essential to evaluate their performance under real wastewater conditions, which often involve complex contaminants. Integrating these hydrogels with technologies such as membrane filtration and photocatalysis could broaden their applications and support sustainable wastewater treatment. However, challenges remain, including their effectiveness in diverse wastewater environments, mechanical strength, and stability during repeated use. Additionally, the cost and scalability of producing improved GG hydrogels hinder industrial application. Future research should aim to develop advanced cross-linking techniques and hybrid materials to enhance durability and reusability. Investigating the environmental impact of these hydrogels post-use is also important for ensuring sustainability. Addressing these limitations is crucial for their practical implementation in dye remediation.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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