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Cassia tora Gum: Structural Modification and Pre-Formulation Studies

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Abstract

Background: Natural gums are biodegradable, biocompatible, non-toxic, easily available, and accessible. However, certain associated disadvantages, such as low swelling ability, viscosity, and flow ability, make them unsuitable for pharmaceutical applications. The study aims to modify *Cassia tora* gum (CTG) through cross-linking by exploring the free hydroxyl groups.

Methods: The CTG obtained from the seeds was taken with the cross-linking reagent and were subjected to the synthetic procedure for the preparation of the cross-linked CTG batches. The reagents utilized as cross-linking agents include Borax (B), Epichlorohydrin (ECH), and 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDC). The reagents were utilized at varying concentrations of 1%, 2%, and 3%, with the most optimal concentration selected for the final batch preparation. The envisaged cross-linked gums were characterized by spectral techniques, and evaluated for physical and rheological parameters.

Results: The cross-linked gums were found to possess modified parameters. The CTG-B was found to be the most optimized gum among others, in terms of flowability (1.31±0.02), freeze-thaw stability (84.9%), flocculation efficiency (62.43% turbidity removal), and sedimentation volume (2.15±0.28 mL). In addition, the fabricated gums exhibited distinct surface morphology, suggesting enhanced drug-loading capacity.

Conclusion: Thus, a novel bio-polymeric materials was developed in the study, which demonstrates promising formulation properties as compared to the native gum.

Keywords: Biomedical-pharmaceutical applications, borax, carbodiimide, *Cassia tora* gum, cross-linking, epichlorohydrin

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Introduction

Materials science is a rapidly evolving field, with carbohydrate polymers leading synthetic/petrochemical-based polymers in formulation development [1]. They find wide application in agriculture, biomedical, and pharmaceutical industries [2]. In the pharmaceutical industry, they are a paramount constituent used for controlling the viscosity of solutions, stabilization of suspensions, granulation, film-forming/coating, binding, and thickening[3], gel-forming [4], and controlling solubility in controlled delivery systems [5]. These are also employed as agents in water-purification, wastewater treatment [6], and biodegradable packaging [7].

Bio-polymeric materials have the advantage of interacting with skin surface proteins and lipids and display peculiar physicochemical properties [8]. In addition, they are biodegradable, non-toxic, and biocompatible [9]. However, polymers, particularly those of natural occurrence, have certain associated drawbacks, which include water solubility issues, viscosity, and flowability. The expanding industrial utility of natural gums has led to intensified research into existing gums and their modification procedures. The process of chemical modification, such as cross-linking, may help to overcome drawbacks and enhance the acceptability of these polymers [10].

Cassia tora gum (CTG) is one such naturally occurring polymer. The CTG is a hydrophilic colloid that is obtained from the endosperm of seeds of *Cassia tora* and *Cassia obtusifolia*, belonging to the Leguminosae family [11]. The endosperm of the seed contains numerous polysaccharides possessing the molecular structure of galactomannan. The CTG is a high-molecular-weight polysaccharide that primarily consists of linear chains of 1,4-β-D-mannopyranose units, branched with α-D-galactopyranose at every fifth position, with a total of 7% glucose, 15% galactose, and 78% mannose [12]. It swells in normal water, while upon boiling, it forms a highly viscous aqueous colloid. It forms an aqueous gel when combined with carrageenan or xanthan gum, or other gelling or thickening agents. It is widely used as an emulsifier, a binding agent [13] a thickener, a foam stabilizer, a gelling agent, a diluent, a stabilizing additive, and an agent for moisture retention [14, 15], useful in the pharmaceutical industry. Apart from the pharmaceutical industry, the CTG also finds usage in the food industry as a texturing agent for the preparation of frozen dairy desserts, poultry-meat products [16], and cheese [17]. However, the CTG has associated drawbacks like swellability, viscosity, and flowability. The chemical modifications provide an efficient way to not only overcome the drawbacks associated with the CTG but also to improve its compressibility, stability, retrogradation, and flocculation efficiency [18]. The CTG can be modified by carbamylation, carboxymethylation, cyanoethylation, carbamoyl ethylation, graft co-polymerization [6], and cross-linking.

In the present study, a cross-linking strategy was employed using three different cross-linking reagents, like Borax (B), Epichlorohydrin (ECH), and 1-ethyl-3-(3-dimethyl aminopropyl) carbodiimide (EDC), to test the improvement in the properties of the CTG. The modifications due to cross-linking may either be within the carbohydrate polymer chains or through intermolecular bonds, thereby increasing the crosslinking density with anticipated tuning in the physicochemical properties for applicative needs [19]. The modified CTGs were evaluated to determine the extent of cross-linking and alterations in flow property, compressibility, swellability, viscosity, retrogradation, freeze-thaw stability, and flocculation efficiency. They were also subjected to particle size determination, Scanning Electron Microscopy (SEM), Thermal Gravimetric Analysis (TGA), and Differential Scanning Calorimetry (DSC). The complete instrumental platform helped to identify the cross-linked gum as a new biomaterial of pharmaceutical importance.

Methods

Collection, identification, authentication, and extraction of plant material

The seeds of *Cassia tora* were collected from the local areas of Lucknow, U.P., India in the month of October, 2018. They were identified and authenticated by the National Botanical Research Institute, Lucknow, under Ref. No: NBRI/CIF/666/2018. All the chemicals used in the research were of analytical grade. CTG was isolated from the seeds and purified using simple methods such as washing, filtration and drying as per the method described by Soni and Pal [10], with a percentage yield of 64%.

Syntheses and optimization of cross-linked CTGs

To synthesize the cross-linked carbohydrate polymers, variable concentrations of all three cross-linking reagents were taken [8] (Figure 1). The most optimal concentration of the crosslinkers, based on crosslinking density, was selected for final batch preparation. In addition to the concentration, two more variables, the rpm (rotations per minute) and the reaction time (in minutes), were taken to design the experiment.

Characterization of CTC and cross-linked CTGs

Micrometric studies

The CTG and cross-linked CTGs, namely borax cross-linked CTG (CTG-B), epichlorohydrin cross-linked CTG (CTG-ECH), and 1-ethyl-3-(3-dimethyl aminopropyl) carbodiimide cross-linked CTG (CTG-EDC) were evaluated for various micrometric study parameters like bulk density, tapped density, Carr's compressibility index, Hausner's ratio, and angle of repose by the methods reported in the literature [20, 21].

Solubility Studies

The solubility studies of CTG and cross-linked CTGs were performed in purified water and ethanol.

Particle size, zeta potential, and polydispersity index

Particle size polydispersity index were analyzed using dynamic light scattering (DLS) with a Zetasizer (Nano ZS, Malvern Instruments, UK) at 173°detection angle in an optically homogeneous square polystyrene cuvette. The results were the average of 3 runs, with at least 13 measurements. Before the measurements, all samples were diluted with ultra-purified water to generate a suitable scattering intensity [22]. Zeta potential was determined using the Electrophoretic Light Scattering (ELS) technique (Nano ZS, Malvern Instruments, UK) at a conductivity of 0.009 mS/cm, with suitable dilution in ultra-purified water. The result was an average of 3 runs, with at least 12 measurements.

Scanning electron microscopy (SEM)

The surface morphology of the CTG and the cross-linked CTGs was characterized through a scanning electron microscope (JSM 6490, JEOL, Japan) [23]. Gold sputtering was performed for approximately 5 minutes to achieve a homogeneous coating on the sample and facilitate high-quality photographs. Images were captured at a low accelerating voltage (30kV) with a current of about 80 mA.

Table 1. Different micrometric study parameters of CTG, CTG-B, CTG-ECH, and CTG-EDC.

Parameters	**Results***			
	CTG	**CTG-B**	**CTG-ECH**	**CTG-EDC**
Bulk Density (g/ml)	0.57 ± 0.01	0.45 ± 0.01	0.31 ± 0.01	0.37 ± 0.02
Tapped Density (g/ml)	0.72 ± 0.01	0.58 ± 0.02	0.37 ± 0.02	0.48 ± 0.01
Carr's Compressibility Index (%)	20.09 ± 0.46	24.78 ± 0.64	19.06 ± 0.69	22.13 ±0.91
Hausner Ratio	1.24 ± 0.02	1.31 ± 0.02	1.20 ± 0.03	1.33 ±0.08
Angle of Repose (°)	38.21 ± 0.32	42.93 ± 0.45	36.82 ± 0.60	41.15 ± 0.66

*The values represent mean ± SD (n = 3).

Table 2. Particle size characterization of CTG, CTG-B, CTG-ECH, and CTG-EDC.

Characterization	**CTG**	**CTG-B**	**CTG-ECH**	**CTG-EDC**
Size (-µm)	8.38±0.79	3.14±0.41	8.31±0.87	8.51±0.62
PDI	3.16±0.49	1.58±0.21	3.18±0.76	2.60±0.53
Zeta Potential (mV)	-7.02±1.52	-34.90±2.60	-5.43±1.95	-3.40±2.10

Swelling index (%)

A 50 ml measuring cylinder containing 1 g of each gum powder (raw and cross-linked) was tapped 100 times, after which the initial volume (X_i) was noted. 10 ml of distilled water was added to each gum powder. The new volume (X_v) obtained was recorded after 24 h. This method was repeated in triplicate, and the swelling index was calculated as the ratio of final volume to initial volume.[24]

$$\text{Swelling Index}(\%) = \frac{\text{Xv}}{\text{Xi}} \times 100 \qquad (1)$$

where X_v and X_i are the final volumes of the gum powder and the initial volume of the gum powder.

Sedimentation volume

1 gm of each gum powder (raw and cross-linked) was added to 50 ml of distilled water. The pH of the slurry was adjusted to 7.0 using either 5% (w/w) sodium hydroxide or 5% (w/w) hydrochloric acid solution. It was heated in a boiling water bath for 15 minutes, taking care that the total volume of the slurry remained constant. A 10 ml sample was taken from the slurry and transferred to a centrifuge tube, and centrifuged at 4000 rpm for 15 minutes at room temperature. The clear liquid was decanted, and the volume of the clear liquid was determined [25]. The volume obtained was used to calculate the sedimentation volume using the equation:

$$\text{SV} = 10\text{-V} \qquad (2)$$

where *V* is the volume of the clear liquid (ml).

Flocculation efficiency

The flocculation efficiency of each gum powder (CTG and cross-linked CTGs) and of alum (a commonly used material for purifying turbid water) was studied using the standard jar test procedure. The test protocol was optimized for 1% kaolin suspension in distilled water. Six beakers containing 100 ml kaolin suspension (pH 2.0) each were used, out of which one was kept as a control (without any gum powder), and the other five were fortified with the powdered alum and different doses of the polymers, from 0.5, 1.0, 1.5, and 2.0 ppm. The initial turbidity was measured using a nephelometer/turbidity meter. The solutions were indistinguishably stirred using a jar test apparatus at 300 rpm for 1min, 80 rpm for 5 min, followed by a settling time of 40 min. After 40 minutes of settling, the supernatant samples were drawn from each beaker, and turbidity was measured using a calibrated nephelometer/turbidity meter. Similar experiments on flocculation efficiency were repeated for a kaolin suspension at pH 5.8 (achieved by adding diluted HCl) and 7.0 (achieved by adding dilute NaOH) [26]. The diagrammatic representation of comparative flocculation efficacy has been reported in Figure 4. Based on the initial and final turbidity values at different pH levels, overall flocculation efficiency was calculated as:

$$\%\text{Turbidity removal} = \frac{(\text{Initial turbidity} - \text{final turbidity})}{\text{Initial turbidity}} \times 100 \qquad (3)$$

Retrogradation

1% w/w slurry of each gum powder (raw and cross-linked) was mixed with 50 ml distilled water, followed by gelatinization in a water bath for 10 minutes. The volume was maintained throughout the process. The gum paste was then cooled at 25°C, and the transparency of the supernatant was measured at the variable standing times of 20 minutes, 40 minutes, 60 minutes, 80 minutes, and 100 minutes [27].

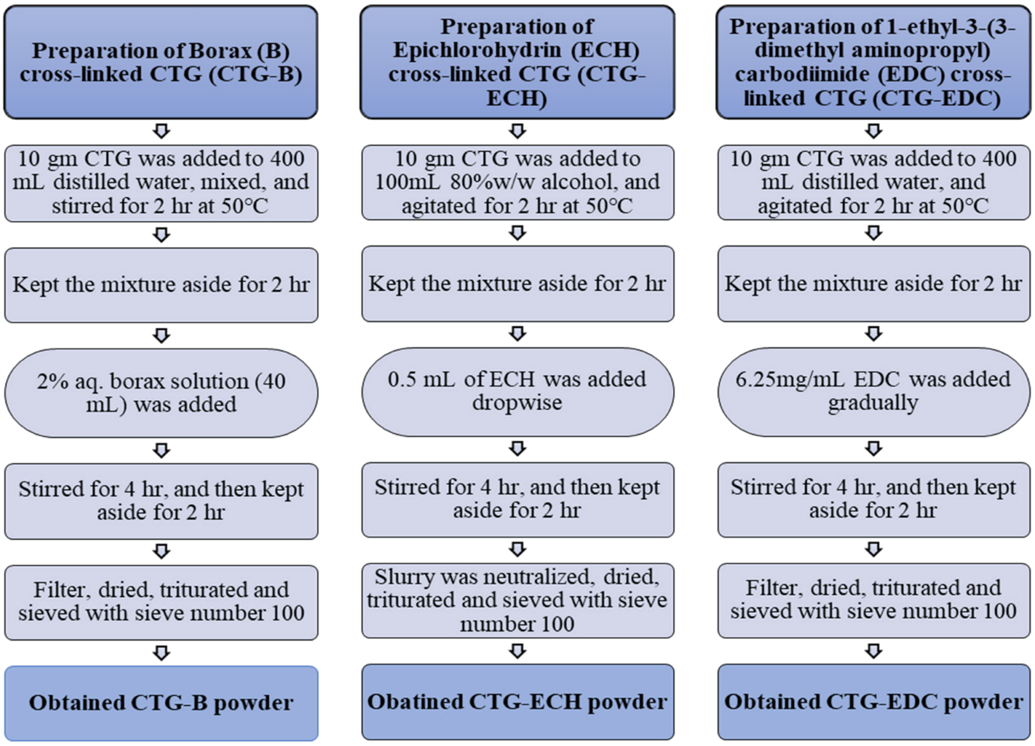

Figure 1: Preparation of the different crosslinked CTG.

Thermal analysis

Thermogravimetric Analysis (TGA)

A sample mass of approximately 5mg was placed in a crucible. The thermogravimetric analysis of CTG and the cross-linked CTGs was performed with a thermogravimetric analyzer (TGA-50 Shimadzu, Japan) at a temperature range of 20-800°C, at a constant heating rate of 10°C/min, under an inert atmosphere (N_2 40 mL/min) [28].

Differential Scanning Calorimetry (DSC)

A sample of approximately 5-10 mg was weighed and placed in a hermetically sealed standard Shimadzu aluminum pan and DSC curves were recorded in the temperature range of 20–300°C at 10°C/min, under an inert atmosphere (N_2 40 mL/min). The analysis was performed in triplicate (DSC-60 plus Shimadzu, Japan) [29]. DSC heat flux mode was used to measure the heat flow difference required to keep the sample and reference at the same temperature, thereby analyzing both endothermic and exothermic events.

Freeze-thaw stability

5 gm of each gum powder (raw and cross-linked) were mixed with distilled water to prepare a paste, which was then gelatinized in a centrifuge tube at 95°C. These were cooled at room temperature for 15 minutes. 10 gm of each gum paste was then taken in a 10 ml centrifuge tube and kept at 4°C for 24 hours, and then at -18°C for another 24 hours. The tubes were removed from the deep freezer and thawed at 50°C in a water bath for 24 hours. It was then centrifuged at 3500 rpm for 15 minutes. The clear liquid obtained was decanted and weighed. The percentage of the separated water was calculated using the given equation [8]:

$$\%\ \text{FTS} = \frac{\text{Weight of decanted liquid}}{\text{Total weight of the paste before centrifugation}} \times 100 \qquad (4)$$

Analytical characterization of CTG and cross-linked CTGs

The cross-linked CTG powders were confirmed by comparing the data of the cross-linked CTG powders with that of the raw CTG utilizing spectroscopic techniques. The FTIR spectrometer (Bruker Alpha-II), Water Alliance e2695/HLC-TQ mass spectrometer, and Bruker Advance 400/AivIII- (300) FT-NMR spectrometer was utilized for the purpose.

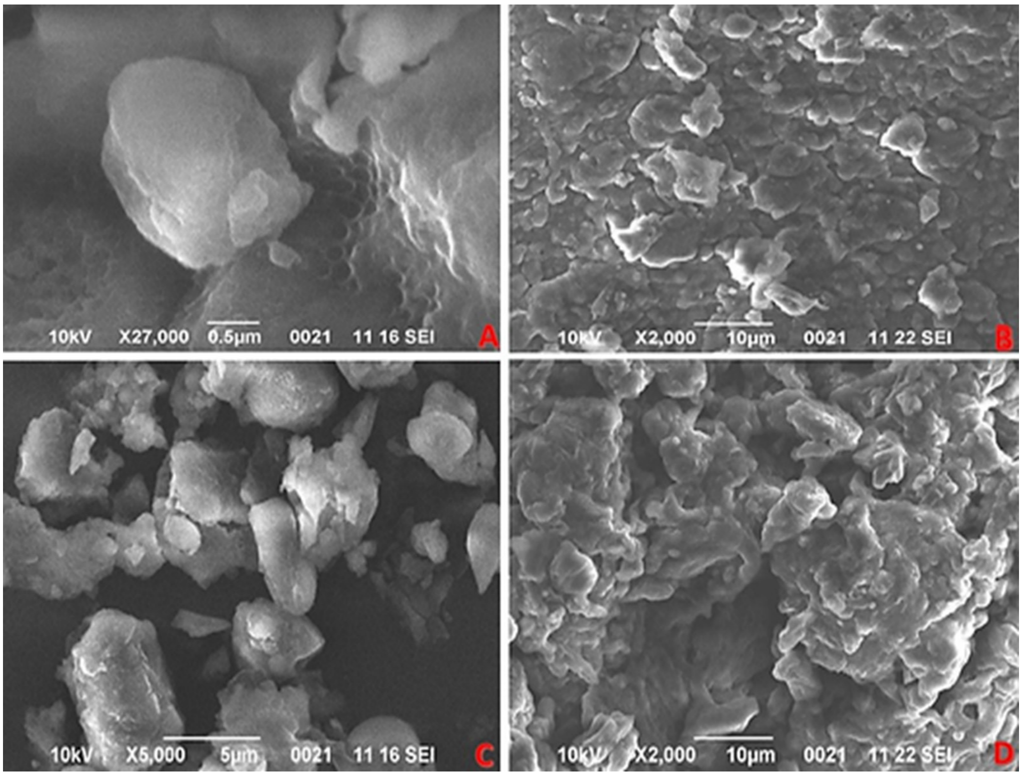

Figure 2: Microscopic morphology (SEM) of (A) CTG, (B) CTG-B, (C) CTG-ECH, and (D) CTG-EDC.

Results

Micrometric Studies

The results of micrometric studies for CTG and cross-linked CTGs are listed in Table 1.

Particle size, zeta potential, polydispersity index (PDI)

The particle size distribution and surface charges of CTG and optimized batches of cross-linked CTGs were determined by the DLS and are as given in Table 2.

Scanning electron microscopy (SEM)

The surface morphology of CTG and cross-linked CTGs was characterized by SEM, and the micrographs obtained are depicted in Figure 2.

Sedimentation volume and percentage swelling index

The calculated sedimentation volume results showed maximum sedimentation of the raw CTG (sedimentation volume = 4.30±0.57 mL). The minimum sedimentation volume was observed in CTG-B (sedimentation volume = 2.15±0.28 mL) as compared to CTG-ECH (sedimentation volume= 3.47±0.5 mL), and CTG-EDC (sedimentation volume = 2.65±0.28 mL). The swelling index was found to be 90.32±1.52, 50.66±0.57, 81.66±0.57, and 63.65±1.15% for CTG, CTG-B, CTG-ECH, and CTG-EDC, respectively, as shown in Figure 3A and 3B.

Retrogradation

The retrogradation of CTG and cross-linked CTGs is shown in Figure 3C. The obtained results showed improved retrogradation values in the cross-linked CTGs. When compared with the data of CTG, it was concluded that the cross-linked CTG powder exhibited stronger retrogradation, which indicates higher cross-linking.

Flocculation efficiency

The flocculation efficiency was calculated as the percent turbidity removal. The experiment was performed at different pHs, viz., 2.0, 5.8, and 7.0, to ensure acidic, neutral, and alkaline conditions, and compared with the standard flocculating agent alum, and the raw CTG, as shown in Figure 4. All the cross-linked CTGs show improved flocculation efficiency at 1.00 ppm as compared to raw CTG. From the data, CTG-B at 1.0 ppm (pH 7.0) was found to be optimal for percent turbidity removal (62.43), and ECH at pH 2.0 exhibited a percent turbidity removal of 18.42 at an optimal concentration of 1.5 ppm.

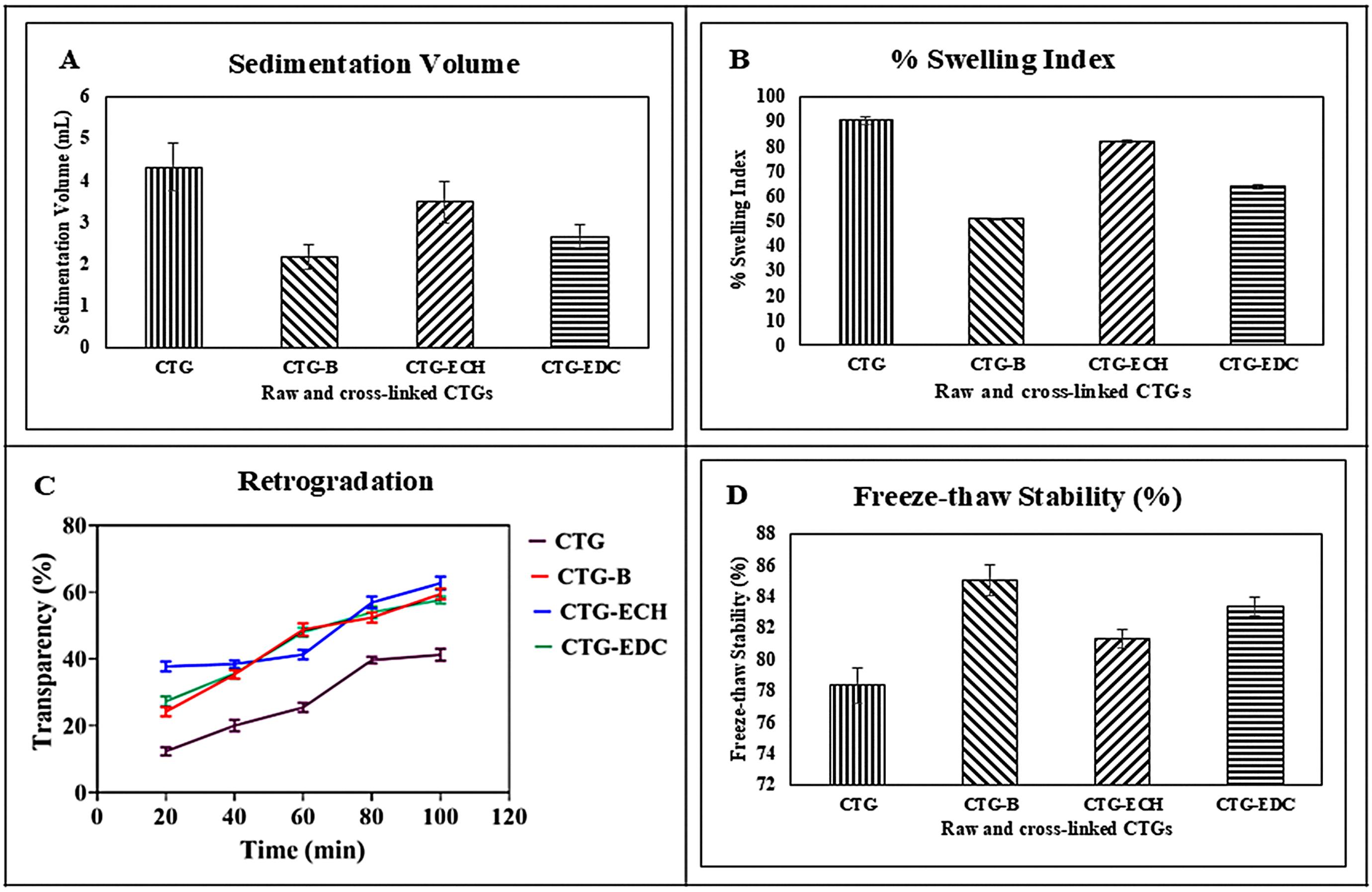

Fig. 3: (A) Sedimentation Volume, (B) Swelling Index, (C) Retrogradation and (D) Freeze-thaw stability studies of CTG, CTG-B, CTG-ECH, and CTG-EDC. The values represent mean ± SD (n = 3).

Freeze-thaw stability

The freeze-thaw stability values for CTG, CTG-B, CTG-ECH, and CTG-EDC were determined as 78.32±1.15, 84.99±1.0, 81.33±0.57, and 83.33±0.57%, respectively, and represented by data given in Figure 3D.

Analytical Characterization of CTG and Cross-linked CTGs

The spectra of the CTG and the cross-linked CTGs as obtained using IR spectroscopy, NMR spectroscopy and Mass spectrometry are as provided in the supplementary materials, S-13 (a) to S-13 (l).

Thermal analysis

Differential Scanning Calorimetry (DSC) and Thermo Gravimetric Analysis (TGA)

According to Figure 5, after crosslinking of CTG, the onset temperature, peak temperature, endset temperature, melting enthalpy, and thermal stability were changed. The onset temperature increased for CTG-EDC, whereas the end-set temperature and melting enthalpy increased for all cross-linked gums.

Discussion

Micrometric studies

The raw CTG and cross-linked CTG-ECH show fair flow, whereas cross-linked CTG-B and CTG-EDC show passable flow, as is indicated by the obtained angle of repose values. The Carr's compressibility index of CTG and CTG-ECH show values of 20.09±0.46 and 19.06±0.69, respectively, denoting that they have fair flowability as compared to CTG-B and CTG-EDC, which have values of 24.78±0.64 and 22.13±0.91, respectively, indicating passable flowability. The Hausner's ratio for CTG and CTG-ECH shows that powders with low inter-particle friction had ratio of 1.24±0.02 and 1.20±0.03, indicating a fair flow property, as compared to the CTG-B and CTG-EDC, which show values of 1.31±0.02 and 1.33±0.08, respectively, indicating passable flow properties. The poor flow properties of cross-linked CTH-B may be due to reduced particle size and increased surface area and roughness, which increases the interparticle friction. Further, solubility studies demonstrate that CTG was soluble in hot water and insoluble in ethanol, whereas crosslinked gums were sparingly soluble in hot water and practically insoluble in ethanol.

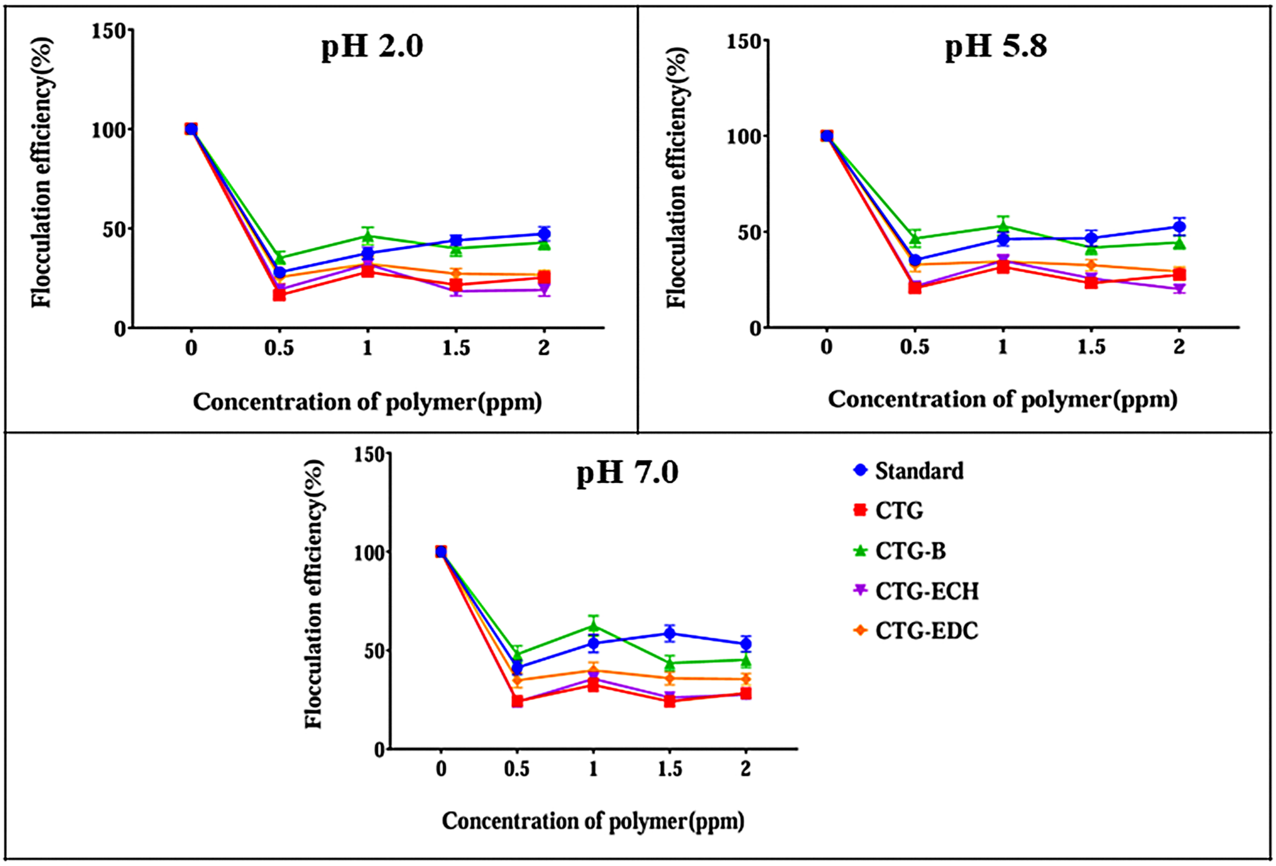

Fig. 4: Comparative flocculation efficiency of standard (alum), CTG, CTG-B, CTG-ECH, and CTG-EDC at different pH (A. pH 2.0; B. pH 5.8; C. pH 7.0)

Particle size, zeta potential, polydispersity index (PDI)

In order to characterize the gums for average particle size and PDI, the DLS method was selected to because of its relatively fast analysis and minimal sample preparation. The optimized batch of CTG-B, compared to the other cross-linked gums, displayed a smaller average particle size of 3.140 µm (Supplementary material, S-12), a zeta potential of -34.90 mV, and a PDI of 1.540 as. The smaller particle size of cross-linked gum exhibits enhanced functional properties due to an increased surface area. The PDI of 1.540 signifies a heterogeneous characteristic of the gum. However, in comparison to the other modified gums and the CTG, it indicates a narrow size distribution (Table 2). The obtained zeta potential greater than ±30 mV indicates a less aggregated, and a more stable crosslinked structure.

Scanning electron microscopy (SEM)

The SEM images of the cross-linked gum reveal a highly irregular and wrinkly surface exhibiting deep crevices (Figure 2), which indicates a high surface-to-volume ratio and an amorphous nature of a porous matrix. Lack of sharp and geometric edges confirms an amorphous nature of the crosslinking that disrupts regular lattice formation, while the dark recessed areas (or voids) visible between the raised section indicate a porous network [30].

Sedimentation volume and percentage swelling index

Sedimentation volume (Figure 3A), is indicative of the extent of the cross-linking in a polymer and is inversely related to it, i.e., the lesser the sedimentation volume of the polymer, the greater will be the cross-linking. This may be because cross-linking hinders water molecules from entering the cross-linked polymer [8]. As observed from the experimental results, the raw CTG displayed maximum sedimentation value of (sedimentation volume = 4.30±0.57 mL), whereas, minimum sedimentation volume was observed in CTG-B (sedimentation volume = 2.15±0.28 mL), indicating a greater extent of crosslinking, compared to CTG-ECH (sedimentation volume = 3.47±0.5 mL), and CTG-EDC (sedimentation volume = 2.65±0.28 mL).

The swelling properties of gum help it be used as an excipient in several formulations. The optimized CTG-B showed a low swelling index as compared to other cross-linked CTGs and raw CTG, which makes it suitable for controlled release [31] formulation by preventing the initial outburst of the drug from formulation due to the high swelling index (Figure 3B).

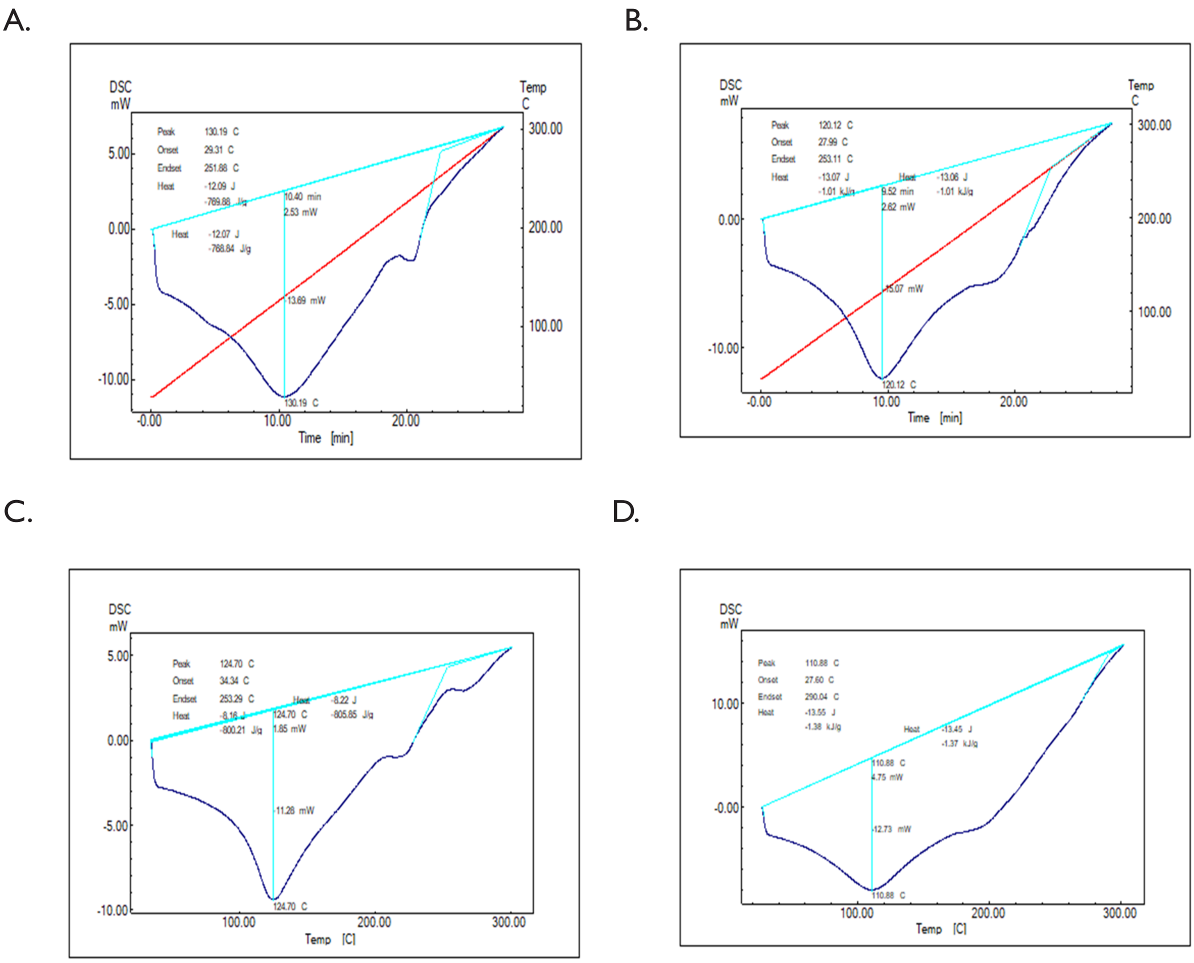

Fig. 5. DSC of (A) CTG, (B) CTG-B, (C) CTG-ECH, and (D) CTG-EDC.

Flocculation efficiency

All the cross-linked CTGs showed significant improvement in flocculation efficiency at 1.00 ppm as compared to the raw CTG.The reason for the improved efficiency of cross-linked polymer over linear polymer can be attributed to their increased hydrodynamic volume and better polymer bridging for the adsorption of different particles [26]. From the data in Figure 4, CTG-B at 1.0 ppm (pH 7.0) was found to be the most optimal (% turbidity removal of 62.43), with the potential to act as a suitable flocculating agent. CTG-ECH at pH 2.0 (% turbidity removal of 18.42) exhibited the potential to be used as a suspending agent at an optimal concentration of 1.5 ppm, as is also supported by its viscosity data.

Retrogradation

The obtained results show improved retrogradation values in cross-linked CTGs. When compared with the data of CTG, it could be concluded that the cross-linked CTG powder exhibited stronger retrogradation, which indicates higher cross-linking [8].

Thermal analysis

Thermogravimetric analysis (TGA) and Differen-tial Scanning Calorimetry (DSC)

The DSC spectra of the CTG (Figure 5A) and the crosslinked CTG-EDC (Figure 5D) show a broad peak, suggesting that moisture or bound solvent was released over a wide temperature range. In the case of crosslinked CTG-B, a comparatively narrower peak is observed, which may be due to reduced size and controlled water absorption. The DSC profiles of CTG, CTG-B, CTG-ECH, and CTG-EDC show an endothermic peak at melting temperature (Tm) of 130.19℃, 120.12℃, 124.70℃, and 110.88℃, respectively. The glass transition temperature (Tg) of all the cross-linked gums was observed in the range of 55-65℃. The peak around 200℃-300℃ represents thermal degradation process. This is usually found in case of carbohydrates, probably due to cleavage of the glycosidic bonds, and charring of the polysaccharide backbone, which releases energy. The event can also be confirmed by the TGA graph, which shows a significant weight loss around 200℃.

The thermogravimetric analysis of raw CTG and the cross-linked gums revealed two distinct zones of mass

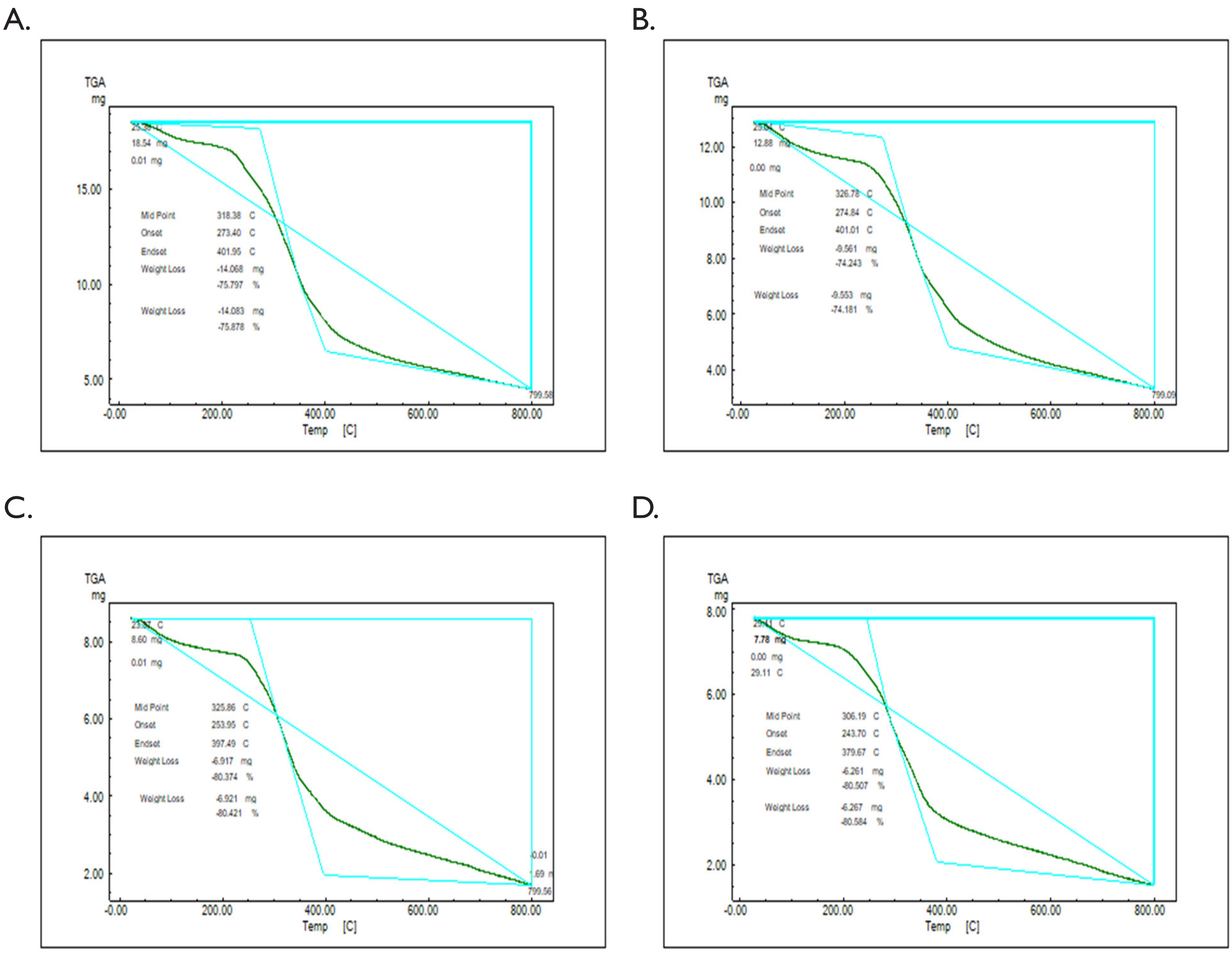

Fig. 6. TGA of (a) CTG, (b) CTG-B, (c) CTG-ECH, and (d) CTG-EDC. Thermal degradation of CTG and cross-linked CTGs was measured using TGA curves, as shown in Fig. 6.

loss. The initial mass loss is observed due to the presence of moisture in the samples,[33] and the melting of the gum. Although the observed maximum rate decomposition temperature and % weight loss in the second stage is due to depolymerization and complete decomposition [23]. As given in Table 3, the onset decomposition temperature, the end decomposition temperature, and the mass loss (%) of crosslinked CTG gum were modified upon crosslinking. The thermal stability is measured primarily by the onset decomposition temperature, which was slightly higher in the CTG-B than in the raw CTG, and the lower mass loss (%) indicated that cross-linking improved the thermal stability of the borax-crosslinked CTG (CTG-B).

Conclusion

In the present study, the CTG was cross-linked in a single-step process under standard laboratory conditions, without the use of any auxiliary. The free hydroxyl groups in the gum's pyranomannose backbone form covalent bonds with the cross-linking agents. Two of the three cross-linking agents, specifically the Borax and the ECH, produced intermolecular cross-linking of the polymeric chains, whereas the cross-linking agent EDC facilitated intramolecular cross-linking.

The structural analysis of chemically modified carbohydrate polymers revealed the potential influence of the size of the cross-linking reagent. The smaller crosslinker exhibited enhanced cross-link density in the modified gum, as evidenced by the findings of the swelling index and cross-linking density. The density of the cross-linkage subsequently improved the stability of the gums, as is evidenced by TGA and DSC analyses. The modified gums exhibited superior characteristics including swelling index, viscosity, flocculation efficiency, retrogradation, and freeze-thaw stability. The CTG-B is supposed to be the most suitably modified biopolymer produced by cross-linking, according to the observations.

The study concludes that the strategy may be useful for design and synthesis of tailor-made natural polymeric materials.

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References

1. Bhatia, S., Natural Polymers vs Synthetic Polymer. In Natural Polymer Drug Delivery Systems: Nanoparticles, Plants, and Algae, Bhatia, S., Ed. Springer International Publishing: Cham, 2016; pp 95-118.
2. Tian, H.; Li, Z.; Lu, P.; Wang, Y.; Jia, C.; Wang, H.; Liu, Z.; Zhang, M., Starch and castor oil mutually modified, cross-linked polyurethane for improving the controlled release of urea. Carbohydr Polym 2021, 251, 117060. https://doi.org/10.1016/j.carbpol.2020.117060
3. Sharma, D.; Sharma, P., Synergistic studies of *Cassia tora* gum with xanthan and guar gum: Carboxymethyl synthesis of cassia gum-xanthan synergistic blend and characterization. Carbohydr Res 2023, 523, 108723. https://doi.org/10.1016/j.carres.2022.108723
4. Gopi, S.; Amalraj, A.; Sukumaran, N. P.; Haponiuk, J. T.; Thomas, S., Biopolymers and Their Composites for Drug Delivery: A Brief Review. Macromol Symp 2018, 380 (1), 1800114. https://doi.org/10.1002/masy.201800114
5. Lohani, A.; Maurya, M.; Kumar, S.; Verma, N., IPN beads prepared by tailoring of *Cassia tora* gum and sodium carboxymethyl cellulose using Al+++ for controlled drug delivery. J Drug Del Sci Tech 2023, 81, 104308. https://doi.org/10.1016/j.jddst.2023.104308
6. Maji, B.; Maiti, S., Chemical modification of xanthan gum through graft copolymerization: Tailored properties and potential applications in drug delivery and wastewater treatment. Carbohydr Polym 2021, 251, 117095. https://doi.org/10.1016/j.carbpol.2020.117095
7. Engel, J. B.; Ambrosi, A.; Tessaro, I. C., Development of biodegradable starch-based foams incorporated with grape stalks for food packaging. Carbohydr Polym 2019, 225, 115234. https://doi.org/10.1016/j.carbpol.2019.115234
8. Hongbo, T.; Yanping, L.; Min, S.; Xiguang, W., Preparation and property of crosslinking guar gum. Polym J 2012, 44 (3), 211-216. https://doi.org/10.1038/pj.2011.117
9. Sivakanthan, S.; Rajendran, S.; Gamage, A.; Madhujith, T.; Mani, S., Antioxidant and antimicrobial applications of biopolymers: A review. Food Res Int 2020, 136, 109327. https://doi.org/10.1016/j.foodres.2020.109327
10. Sharma, B.; Kumar, V.; Soni, P. L., Carbamoylethylation of *Cassia tora* gum. Carbohydr Polym 2003, 54, 143-147. https://doi.org/10.1016/S0144-8617(03)00132-2
11. Lee, M.-J.; Nho, J.-H.; Yang, B.-D.; Park, H.; Lee, H.-J.; Lee, K.-H.; Jang, J.-H.; Jung, H.-K.; Kim, S.-R.; Cho, H.-W.; Park, H.-S.; Lim, J.-O.; Kim, J.-C., Subchronic toxicity evaluation of ethanol extract of *Cassia tora* L. seeds in rats. Reg Toxicol Pharmacol 2019, 109, 104487. https://doi.org/10.1016/j.yrtph.2019.104487
12. Cao, L.; Liu, W.; Wang, L., Developing a green and edible film from Cassia gum: The effects of glycerol and sorbitol. J Cleaner Prod 2018, 175, 276-282. https://doi.org/10.1016/j.jclepro.2017.12.064
13. Nawabjohn, M. S.; Sivaprakasam, P.; Anandasadagopan, S. K.; Begum, A. A.; Pandurangan, A. K., Green Synthesis and Characterisation of Silver Nanoparticles Using *Cassia tora* Seed Extract and Investigation of Antibacterial Potential. Appl Biochem Biotech 2022, 194 (1), 464-478. https://doi.org/10.1007/s12010-021-03651-4
14. Jaramillo-Quiceno, N.; Duque Carmona, A. S.; Serna, J. S.; Carmona, D. M.; Torres-Taborda, M.; Hincapié-Llanos, G.A.; Marín, J. F. S.; Álvarez-López, C., Enhancing soil water retention and plant growth with thermal crosslinked silk sericin-based hydrogel. J Environ Chem Eng 2024, 12 (2), 112260. https://doi.org/10.1016/j.jece.2024.112260
15. Labowska, M. B.; Skrodzka, M.; Sicińska, H.; Michalak, I.; Detyna, J., Influence of Cross-Linking Conditions on Drying Kinetics of Alginate Hydrogel. Gels 2023, 9 (1). https://doi.org/10.3390/gels9010063
16. Salimbahrami, S. N.; Ghorbani-HasanSaraei, A.; Tahermansouri, H.; Shahidi, S.-A., Synthesis, optimization via response surface methodology, and structural properties of carboxymethylcellulose/curcumin/graphene oxide biocomposite films/coatings for the shelf-life extension of shrimp. Int J Bio Macromol 2023, 253, 126724. https://doi.org/10.1016/j.ijbiomac.2023.126724
17. Sharma, D.; Kumar, V.; Nautiyal, R.; Sharma, P., Synthesis and characterization of quaternized *Cassia tora* gum using Taguchi L'16 approach. Carbohydr Polym 2020, 232, 115731. https://doi.org/10.1016/j.carbpol.2019.115731
18. Partis, M. D.; Griffiths, D. G.; Roberts, G. C.; Beechey, R. B., Cross-linking of protein by ω-maleimido alkanoyl N-hydroxysuccinimido esters. J Protein Chem 1983, 2 (3), 263-277. https://doi.org/10.1007/BF01025358
19. Singh, M.; Kanoujia, J.; Parashar, P.; Arya, M.; Tripathi, C. B.; Sinha, V. R.; Saraf, S. K.; Saraf, S. A., Assessment of improved buccal permeation and bioavailability of felodipine microemulsion-based cross-linked polycarbophil gel. Drug Deliv Transl Res 2018, 8 (3), 591-601. https://doi.org/10.1007/s13346-018-0489-5
20. Pawar, H.A.; Lalitha, K. G., Extraction, Characterization, and Molecular Weight Determination of *Senna tora* (L.) Seed Polysaccharide. Int J Bio 2015, 2015, 928679. https://doi.org/10.1155/2015/928679
21. Maheshwari, R.; Todke, P.; Kuche, K.; Raval, N.; Tekade, R. K., Chapter 17 - Micromeritics in Pharmaceutical Product Development. In Dosage Form Design

Considerations, Tekade, R. K., Ed. Academic Press: 2018; pp 599-635. https://doi.org/10.1016/B978-0-12-814423-7.00017-4

22. Lei, M.; Huang, W.; Sun, J.; Shao, Z.; Chen, Z.; Chen, W., Synthesis and characterization of high-temperature self-crosslinking polymer latexes and their application in water-based drilling fluid. Powder Technology 2021, 389, 392-405. https://doi.org/10.1016/j.powtec.2021.05.045
23. Pal, R. R.; Kumar, D.; Raj, V.; Rajpal, V.; Maurya, P.; Singh, S.; Mishra, N.; Singh, N.; Singh, P.; Tiwari, N.; Saraf, S. A., Synthesis of pH-sensitive crosslinked guar gum-g-poly(acrylic acid-co-acrylonitrile) for the delivery of thymoquinone against inflammation. Int J Biol Macromol 2021, 182, 1218-1228. https://doi.org/10.1016/j.ijbiomac.2021.05.072
24. Eshun Oppong, E.; Kuntworbe, N.; Asantewaa Osei, Y.; Ofori-Kwakye, K.; Adi-Dako, O.; Obese, E., Physicochemical characterisation of Piptadeniastrum africana (Hook. F.) gum, a potential pharmaceutical excipient. Sci Afr 2021, 13, e00925. https://doi.org/10.1016/j.sciaf.2021.e00925
25. Raina, C. S.; Singh, S.; Bawa, A. S.; Saxena, D. C., Some characteristics of acetylated, cross-linked and dual modified Indian rice starches. Eur Food Res Tech 2006, 223 (4), 561-570. https://doi.org/10.1007/s00217-005-0239-z
26. Thombare, N.; Jha, U.; Mishra, S.; Siddiqui, M. Z., Borax cross-linked guar gum hydrogels as potential adsorbents for water purification. Carbohydr Polym 2017, 168, 274-281. https://doi.org/10.1016/j.carbpol.2017.03.086
27. Sobolewska-Zielińska, J.; Fortuna, T. In Retrogradation of starches and maltodextrins of origin various, Acta Sci Pol Technol Aliment 2010, 9(1), 71-81.
28. Cheng, C.; Sun, G.; Khoshdel, E.; Wooley, K. L., Well-Defined Vinyl Ketone-Based Polymers by Reversible Addition-Fragmentation Chain Transfer Polymerization. J Am Chem Soc 2007, 129 (33), 10086-10087. https://doi.org/10.1021/ja073541y
29. Komeda, M.; Nagayama, S.; Yoshida, Y.; Endo, T., Synthesis of polymethacrylate-bearing benzocyclobutene structure and extension to networked polymer based on thermal isomerization. J Polym Sci Part A: Polym Chem 2019, 57 (21), 2175-2180. https://doi.org/10.1002/pola.29495
30. Ribeiro, F. W. M.; Laurentino, L. d. S.; Alves, C. R.; Bastos, M. d. S. R.; Costa, J. M. C. d.; Canuto, K. M.; Furtado, R. F., Chemical modification of gum arabic and its application in the encapsulation of Cymbopogon citratus essential oil. J Appl Polym Sci 2015, 132 (8). https://doi.org/10.1002/app.41519
31. Hani, U.; Mahammed, N.; Reshma, T.; Talath, S.; Wali, A. F.; Aljasser, A.; Al Fatease, A.; Alamri, A. H.; Khan, S., Enhanced colon-targeted drug delivery through development of 5-fluorouracil-loaded cross-linked mastic gum nanoparticles. Sci Rep 2025, 15 (1), 18355. https://doi.org/10.1038/s41598-025-03533-3
32. Amangah, M.; Salami-Kalajahi, M.; Roghani-Mamaqani, H., Nanoconfinement effect of graphene on thermophysical properties and crystallinity of matrix-grafted graphene/crosslinked polysulfide polymer nanocomposites. Diam Relat Mater 2018, 83, 177-183. https://doi.org/10.1016/j.diamond.2018.02.012
33. Hongbo, T.; Yanping, L.; Wen, Z.; Siqing, D., Synthesis, Optimization, Property, Characterization, and Application of Dialdehyde Cross-Linking Guar Gum. Int J Polym Sci 2016, 2016, 6482461. https://doi.org/10.1155/2016/6482461