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Review Article

Green Polymers for Human Welfare: Exploring Plant-Derived Natural Gums as Safe Polysaccharides in Sustainable Drug Delivery Systems

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Abstract

Natural gums derived from plants are gaining traction as valuable biopolymers in the creation of safe, sustainable, and effective pharmaceutical products. These polysaccharides such as guar gum, xanthan gum, locust bean gum, and gum karaya possess favorable physicochemical attributes, including high viscosity, swelling properties, and the ability to form films, which allow them to function as matrix formers, binders, and release retardants in both oral and innovative drug delivery systems. In contrast to synthetic polymers, natural gums demonstrate biocompatibility, biodegradability, renewability, and cost efficiency. This review focuses on the structural features, formulation benefits, and limitations of plant-based gums, highlighting their utility in both traditional and advanced drug delivery methods. It also examines strategies for chemical modifications, smart polymer characteristics for targeted release, and recent studies that underscore their significance in sustained and targeted drug delivery. The paper concludes by discussing future research avenues and the promise of these eco-friendly polymers to enhance human well-being and drive sustainable innovations in pharmaceuticals.

Keywords: Natural gums, Green polymers, Biopolymers, Drug delivery systems, Controlled release, Pharmaceutical applications

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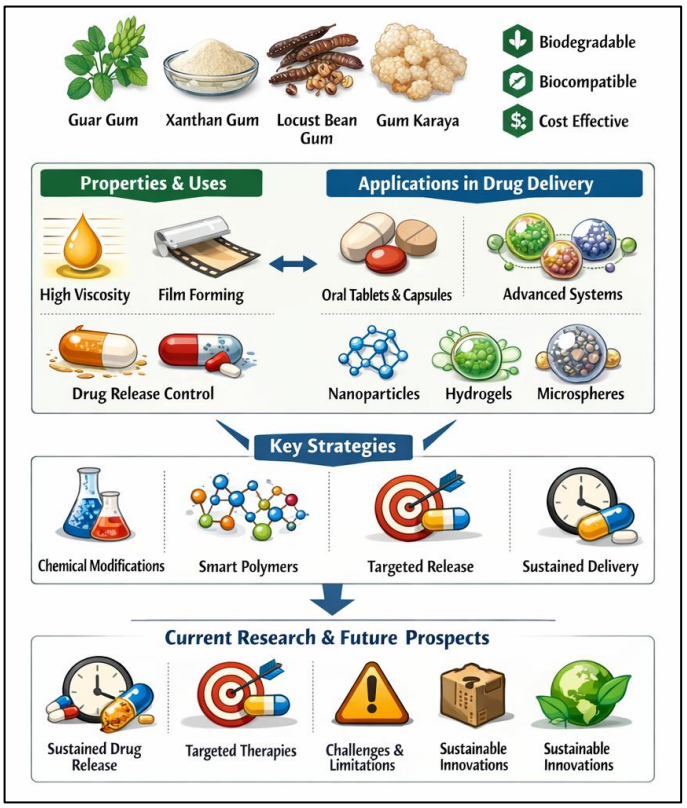
Graphical Abstract



1. Introduction

The growing emphasis on sustainability and patient safety has accelerated interest in natural polymers as alternatives to synthetic excipients in pharmaceutical formulations. Synthetic polymers, although widely used, may present issues related to toxicity, non-biodegradability, and environmental persistence. In contrast, natural polymers derived from plant sources are biodegradable, renewable, and generally recognized as safe, making them attractive candidates for drug delivery applications[1,2]. Plant-derived natural gums are complex polysaccharides obtained from plant exudates (gum arabic, karaya), seeds (guar gum, locust bean gum), or fruits and barks. These materials have long been used in food and traditional medicine and are now increasingly explored as pharmaceutical excipients due to their functional versatility[3]. Their ability to hydrate, swell, and form viscous gels enables them to function as binders, disintegrants, matrix formers, stabilizers, and release-modifying agents in dosage forms[4]. Natural gums possess hydroxyl-rich polysaccharide backbones that allow hydrogen bonding and chemical derivatization, facilitating their application in controlled and targeted drug delivery systems[5]. Several studies have demonstrated the effectiveness of gums such as guar gum and pectin in colon-specific drug delivery due to their susceptibility to degradation by colonic

microflora[6]. Similarly, xanthan and karaya gums have been used to develop hydrophilic matrices capable of sustaining drug release over extended periods[7]. This review aims to provide a comprehensive evaluation of plant-derived natural gums as green polymers for pharmaceutical use. It discusses their physicochemical properties, formulation advantages and challenges, chemical modification strategies, and applications in conventional and novel drug delivery systems. By synthesizing evidence from well-established scientific literature, the article underscores the potential of natural gums to support sustainable pharmaceutical development and improve human welfare.

2. Physicochemical Characteristics of Plant-Derived Natural Gums

Natural gums are high-molecular-weight polysaccharides composed mainly of monosaccharides such as galactose, mannose, arabinose, rhamnose, and glucuronic acid. Their molecular structure and composition significantly influence their functional performance in pharmaceutical formulations[3].

2.1 Composition and Structure: In terms of composition and structure, most natural gums are composed of complex hetero polysaccharide chains with β-(1→4) or α-(1→6) glycosidic linkages. These structures are rich in hydroxyl groups, which enable extensive hydrogen bonding with water and other polymer chains, thereby promoting gel formation and effective film-coating behavior. Such molecular interactions are fundamental to their ability to form stable matrices for drug encapsulation and controlled release[5].

2.2 Viscosity and Swelling Behaviour: Gums such as guar gum and xanthan gum readily hydrate in aqueous environments, forming highly viscous systems that are particularly advantageous for sustained- and controlled-release drug delivery. Their swelling behavior plays a critical role in regulating drug release kinetics, as it governs both matrix erosion and diffusion pathways, allowing for prolonged therapeutic action[7].

2.3 Solubility and pH Sensitivity: pH sensitivity is also an important property of certain gums, including pectin and gum karaya, which exhibit solubility changes depending on the surrounding pH. This characteristic is especially valuable in the design of site-specific delivery systems, such as colon-targeted or gastric-retentive formulations, where drug release can be triggered selectively in specific regions of the gastrointestinal tract[6].

2.4 Stability and Functional Properties: Natural gums exhibit multifunctional behavior in pharmaceutical formulations, acting as binders, emulsifiers, suspending agents, and film formers. Their stability is influenced by moisture content, microbial load, and processing conditions. Proper drying, purification, and storage are essential to maintain their physicochemical integrity and prevent microbial contamination[8]. Despite being thermally less stable than synthetic polymers, many natural gums retain adequate stability under standard pharmaceutical processing conditions, including wet granulation and compression[9].

2.5 Modulation of Properties: Plant-derived gums possess diverse functional properties, including binding, emulsifying, and stabilizing abilities, which are essential for the formulation of tablets, emulsions, and suspensions. These multifunctional roles make natural gums versatile excipients in modern pharmaceutical dosage forms. The functional properties of plant gums can be modulated through polymer blending or chemical modification. Blending with polymers such as hydroxypropyl methylcellulose (HPMC), alginate, or chitosan improves mechanical strength, reproducibility, and drug release control[10]. These adaptable physicochemical characteristics make natural gums suitable candidates for a wide range of drug delivery systems.

3. Advantages and Limitations of Natural Gum Polysaccharides

3.1 Advantages

Biocompatibility and Safety: Their biocompatibility and biodegradability ensure that they are safe for human use and can be easily metabolized or eliminated from the body without causing adverse effects[1,3].

Biodegradability and Environmental Sustainability: These polymers undergo enzymatic degradation into harmless by-products, reducing environmental burden and supporting green pharmaceutical practices[2].

Renewable and Economical: Another important advantage is their renewability, as these polymers are derived from abundant plant sources, making them sustainable and environmentally responsible[4].

Functional Versatility: Their functional diversity, including excellent swelling, binding, and film-forming properties, allows them to perform multiple roles such as matrix formers, stabilizers, and release modifiers in drug delivery systems[7].

Mucoadhesive Properties: Furthermore, their mucoadhesive nature enhances drug residence time at mucosal surfaces, improving drug absorption and bioavailability in systems such as buccal, nasal, and ocular delivery[11].

3.2 Limitations

Batch-to-Batch Variability: One major concern is variability, since their physicochemical properties may differ depending on plant source, geographical location, and environmental conditions, leading to batch-to-batch inconsistency[8].

Microbial Contamination: They are also prone to microbial contamination, which necessitates proper purification, drying, and sterilization to ensure safety and stability[9].

Mechanical Weakness: In addition, many natural gums exhibit limited mechanical strength, making them less suitable for high-stress formulations unless modified through cross-linking or blending with other polymers[10].

pH Sensitivity: Another limitation is their pH sensitivity, as some gums show variable performance under

different gastrointestinal conditions, which can affect drug release profiles[11].

Storage Instability: Storage instability is a concern, since their hygroscopic nature makes them sensitive to moisture, potentially reducing shelf life and altering functional performance over time.

Table 1: Tabular form of advantages and limitations

Advantages	Limitations
Biocompatibility and Biodegradability	Variability
Renewability	Microbial Contamination
Non-toxicity	Limited Mechanical Strength
Eco-friendliness	pH Sensitivity
Functional Diversity	Storage Instability
Economic Benefits	
Mucoadhesive Nature	

4. Applications in Conventional and Novel Drug Delivery Systems

4.1 Sustained-Release Matrix Systems: In sustained-release matrix tablets, gums such as guar gum and xanthan gum are commonly employed as matrix formers, where their high swelling and gel-forming capacity helps to regulate drug diffusion and matrix erosion, thereby providing prolonged and controlled release of drugs such as diclofenac sodium[7,13].

4.2 Mucoadhesive Drug Delivery Systems: In mucoadhesive drug delivery systems, natural gums including karaya and cashew gum exhibit strong adhesive interactions with mucosal surfaces. This property is particularly beneficial for buccal and vaginal formulations, as it enhances the residence time of the dosage form at the site of absorption, leading to improved drug bioavailability and therapeutic efficacy[11,14].

4.3 Gastro-Retentive and Floating Systems: In gastro-retentive or floating drug delivery systems, gums like karaya and tamarind gum are employed to increase buoyancy and gastric residence time. These properties are useful for drugs that are preferentially absorbed in the stomach or upper gastrointestinal tract, enabling sustained release and improved therapeutic outcomes[15].

4.4 Colon-Targeted Drug Delivery: Finally, natural polysaccharides such as guar gum and pectin play a crucial role in colon-targeted drug delivery. These polymers resist digestion in the upper gastrointestinal tract but are selectively degraded by colonic microflora, allowing for site-specific drug release in the colon. This approach is particularly valuable for the treatment of local disorders such as ulcerative colitis and colorectal cancer[6,16].

4.5 Hydrogels, Films, and Particulate Systems: Natural gums are also widely used in the preparation of hydrogels and films. For instance, aloe gum and gum arabic can form bioadhesive and flexible hydrogel networks that are suitable for wound healing, transdermal patches, and other topical applications. These systems not only provide controlled drug release but also promote moisture retention and tissue regeneration[17,18].

4.6 Microspheres and Nanoparticles: In advanced delivery platforms, natural gums such as locust bean gum and okra mucilage have been successfully utilized in the fabrication of microspheres and nanoparticles. Their biocompatibility and ability to encapsulate both hydrophilic and hydrophobic drugs make them ideal candidates for microencapsulation and nanoparticulate drug delivery, offering enhanced stability, targeted delivery, and reduced side effects[19].

5. Chemical Modification and Functionalization of Natural Gums

Chemical modification and functionalization play a crucial role in enhancing the physicochemical and mechanical properties of natural gums, thereby expanding their applicability in advanced drug delivery systems. Chemical derivatization enhances the physicochemical and mechanical properties of natural gums.

5.1 Carboxymethylation and Acetylation:

Furthermore, chemical treatments such as carboxymethylation and acetylation alter the polarity and hydrophilicity of gum molecules, leading to changes in solubility and swelling characteristics. These modifications make natural gums more pH-responsive and suitable for site-specific drug delivery, particularly in gastrointestinal applications[20].

5.2 Cross-Linking:

Through cross-linking**,** the polymer chains are interconnected to form a more stable three-dimensional network, which significantly improves mechanical strength, reduces rapid dissolution, and allows better control over drug release rates[21].

5.3 Graft Copolymerization:

Another important strategy is graft copolymerization**,** in which functional monomers are chemically attached to the backbone of natural gums. This modification introduces new functional groups that can tailor solubility, improve responsiveness to environmental stimuli such as pH or temperature, and enhance compatibility with both hydrophilic and hydrophobic drugs. Such functionalization enables the design of smart delivery systems with controlled and targeted release behavior[22].

5.4 Blending:

In addition**,** polymer blending is widely used, where natural gums are combined with polymers like chitosan, HPMC, or alginate to improve bioadhesive properties, mechanical integrity, and overall formulation stability. Collectively, these chemical and physical modifications transform ordinary natural gums into versatile and

high-performance biomaterials suitable for modern pharmaceutical and biomedical applications[23,24].

6. Smart and Site-Specific Drug Delivery Systems

Natural gums can be effectively transformed into smart polymers capable of responding to various physiological stimuli such as pH, temperature, and enzymatic activity, making them highly suitable for site-specific drug delivery systems. These stimulus-responsive properties allow natural gums to regulate drug release in a controlled manner depending on the biological environment, thereby improving therapeutic efficacy and minimizing systemic side effects[25].

6.1 *Stomach-Targeted Systems:* In stomach-targeted delivery systems, gums such as karaya and xanthan exhibit high swelling and gel-forming behavior in acidic conditions, which helps in prolonging gastric residence time. This characteristic is particularly useful for drugs that require extended exposure in the stomach or are primarily absorbed in the upper gastrointestinal tract. The swollen polymer matrix acts as a barrier to drug diffusion, ensuring sustained release and improved bioavailability[26].

6.2. *Intestinal Targeting:* For intestinal targeting, chemically modified natural gums are designed to remain relatively stable in acidic gastric conditions but dissolve or swell in slightly alkaline environments. This enables controlled drug release in the small intestine, where optimal absorption occurs for many drugs. Such pH-responsive behavior enhances drug stability and prevents premature release in the stomach[27].

6.3 *Colon-Specific Systems:* In colon-specific drug delivery, polysaccharides such as guar gum, pectin, and locust bean gum play a vital role due to their susceptibility to degradation by colonic microflora. These polymers resist digestion in the upper gastrointestinal tract but undergo enzymatic breakdown in the colon, leading to localized and targeted drug release. This strategy is particularly beneficial in the treatment of diseases such as ulcerative colitis, Crohn's disease, and colon cancer, where site-specific drug action can significantly improve therapeutic outcomes while reducing adverse effects[28]. These smart systems enhance therapeutic efficiency while minimizing systemic side effects.

7. Recent Literature Overview and Comparative Insights

Recent studies consistently demonstrate that guar gum, xanthan gum, pectin, and gum karaya exhibit excellent swelling, mucoadhesion, and sustained-release properties. Chemically modified and blended formulations show improved reproducibility and mechanical strength compared with native gums. Comparative analyses suggest that natural gums can effectively replace synthetic polymers in many controlled-release applications without compromising performance[7,10,13].

8. Future Prospects and Challenges

Future research should focus on standardization, large-scale processing, and regulatory acceptance of natural gums. Integration with nanotechnology, polymer chemistry, and computational formulation design may further enhance their potential for application. Addressing challenges related to variability, microbial safety, and scalability will be essential for their widespread industrial adoption[2,21].

Table 2: Represents Research on Dosage Forms Using Natural Gums

Natural Gum / Polymer	Dosage Form / Application	Model Drug / System	Key Findings / Notes	Ref
Okra gum + Locust bean gum	Gastroretentive sustained-release tablets	Ziprasidone HCl	Combined natural gums with HPMC provided buoyancy and sustained release over ~24 h.	29
Xanthan gum	Matrix sustained-release tablets	Metoprolol	Controlled release via swelling matrix (slower drug diffusion).	30
Guar gum	Matrix sustained-release tablets	Metoprolol	Guar provided sustained release with desirable matrix integrity.	30
Honey locust gum (Gleditsia triacanthos)	Matrix tablets	Theophylline	Gum acted as a hydrophilic matrix controlling release.	31
Xanthan + Guar gum blend	Matrix sustained-release tablets	Tramadol hydrochloride	Gum blend improved swelling and modulated release kinetics.	32
Natural gum polysaccharides (review)	Various dosage forms	—	Natural gum polysaccharides overview with emphasis on biodegradability & delivery potential.	19

Natural gums in effervescent floating systems	Floating matrix tablets	Baclofen	Natural gums contributed to buoyancy and sustained release.	33
Natural gums &mucilages (review)	Broad pharma excipient roles	—	Highlights gums for SR, mucoadhesion, binding, and matrix systems.	34
Natural gum (Terminalia elliptica) in pulsatile system	Pulsatile drug delivery tablets	Atenolol	Gum from *Terminalia elliptica* used in press-coated tablets showing ~7 h lag time followed by rapid release potential for chronotherapy systems.	35
Modified & natural gums (review)	Matrix and other dosage forms	—	Reviews techniques for modifying mucilage/gums to tailor hydrophilicity and drug release (e.g., extended release, matrix forming).	36

9. Conclusion

Plant-based natural gums have emerged as flexible and sustainable biopolymers with great potential to change modern pharmaceutical formulations and drug delivery systems. Their natural properties include high viscosity, swelling capacity, film-forming abilities, and biocompatibility. These characteristics allow them to serve effectively as matrix formers, binders, and agents for modifying release in both traditional and newer dosage forms. Compared to synthetic polymers, natural gums offer extra benefits such as renewability, biodegradability, low toxicity, and cost-effectiveness. These features make them suitable for the growing global demand for eco-friendly pharmaceutical materials. This review highlights that while there are some drawbacks, such as variability between batches and sensitivity to microbial contamination, these issues can be largely addressed through purification methods, chemical changes, and polymer blending strategies. The development of smart, responsive gum-based systems further improves their application in targeted and extended drug delivery, potentially leading to better therapeutic outcomes and enhanced patient adherence. In conclusion, plant-derived gums present a promising option as excipients that can promote sustainable innovation in pharmaceuticals. Ongoing research into their structural improvement, functional changes, and large-scale production will be vital to unlock their full potential. With the rising emphasis on eco-friendly technologies and patient-centered formulations, natural gums are poised to make a significant impact on the future of drug delivery and support the sustainability of global healthcare.

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