

## REVIEW ARTICLE



# Functional and Physicochemical Properties of *Abelmoschus esculentus* Mucilage as a Versatile Biopolymer for Pharmaceutical and Nutraceutical Applications

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**Abstract:** Natural plant-derived polysaccharides are gaining prominence as green alternatives to synthetic polymers in pharmaceutical and food sciences. *Abelmoschus esculentus* mucilage, a complex carbohydrate composed primarily of rhamnose, galactose, and galacturonic acid, presents a suite of physicochemical properties ideal for modern formulation challenges. Its high swelling capacity, pH-dependent viscosity, and biocompatibility facilitate its role as a robust binder and a rate-retardant matrix in controlled-release systems. Extraction techniques, ranging from conventional aqueous maceration to solvent-assisted precipitation, significantly influence the polymer's molecular weight and subsequent functional performance. Apart from its utility as a pharmaceutical excipient, the gum exhibits significant therapeutic potential, including antioxidant, antidiabetic, and anti-adhesive activities against gastric pathogens like *Helicobacter pylori*. In food technology, it serves as a natural stabilizer and emulsifier, enhancing the textural and nutritional profiles of functional foods. Systematic characterization via thermal analysis and rheological profiling confirms its stability and versatility. The synergy between its mechanical integrity and biological activity establishes okra gum as an important excipient in the transition toward green pharmaceutical manufacturing and personalized nutraceutical development. Its ability to modulate drug release kinetics, particularly for high-dose medications like Metformin hydrochloride, shows its practical utility in improving patient adherence and therapeutic outcomes. Okra gum meets the rigorous demands of global regulatory standards for pharmaceutical adjuvants as a non-toxic, biodegradable, and cost-effective material.

**Keywords:** *Abelmoschus esculentus*; Natural excipient; Controlled drug delivery; Polysaccharide; Bio-adhesive

## 1. Introduction

Natural polymers derived from botanical sources are high molecular weight, water-soluble macromolecules characterized by monosaccharide units interconnected via glycosidic linkages. The demand for these natural gums has escalated within the pharmaceutical sector due to their inherent biodegradability, low toxicity, and capacity to modulate drug release profiles in sophisticated delivery systems [1]. *Abelmoschus esculentus*, a prominent member of the Malvaceae family, is widely recognized as a versatile vegetable crop cultivated extensively in tropical and subtropical climates. Apart from its dietary value, the plant is a significant source of a polysaccharide-rich mucilage known as okra gum.

The primary value of okra gum lies in its role as a multifunctional excipient. In solid oral dosage forms, its hydrophilic nature allows for the formation of a viscous gel layer upon hydration, which acts as a diffusion barrier to retard the release of active pharmaceutical ingredients (APIs). This mechanism is particularly advantageous for sustained-release formulations, where increasing the biological half-life of a drug is necessary to reduce dosing frequency [2, 3]. The mucoadhesive properties of the gum permit localized drug delivery at specific physiological sites, enhancing bioavailability.

Recent investigations have focused on the application of okra gum in compression-coated tablets and gastro-retentive systems. For instance, drugs with narrow absorption windows or short half-lives, such as Metformin hydrochloride a biguanide used in the management of Type II diabetes require specialized delivery strategies. Metformin possesses an oral bioavailability of approximately 40–60% and a plasma elimination half-life of 6 hours, necessitating multiple daily doses [4]. Incorporating okra gum into the matrix of such medications provides a controlled release mechanism that maintains therapeutic plasma levels and improves patient compliance.

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## 2. Botanical Source and Geographical Distribution

### 2.1. Biological Classification and Morphology

*Abelmoschus esculentus* (L.) Moench is an erect, annual or perennial herbaceous plant that can reach heights of up to 4 meters. It is characterized by its hairy stems and large, palmate leaves. The fruit, commonly referred to as "lady's finger" or "okra," is a pentagonal to round capsule containing numerous globose seeds [3]. The plant thrives in warm environments and exhibits notable resilience to drought and heat, though it remains highly sensitive to frost and chilling temperatures.

### 2.2. Global Cultivation and Traditional Nomenclature

The geographical footprint of okra spans across various continents, with commercial production concentrated in India, Pakistan, Bangladesh, West Africa, Brazil, and the southern United States [5, 6]. The term "okra" itself has East African origins, reflecting its historical migration and integration into diverse cuisines and traditional medicine systems. Its widespread availability and ease of cultivation make it a cost-effective raw material for the industrial extraction of pharmaceutical-grade mucilage.

## 3. Chemical Composition and Structural Characteristics

### 3.1. Nutritional and Phytochemical Properties

The fruits of *A. esculentus* are nutrient-dense, providing essential minerals such as calcium, potassium, phosphorus, and magnesium, alongside vitamins and dietary fiber. The dietary fiber content is approximately 8.16 g per 100 g of fresh weight, which contributes to the viscous nature of the pods [4]. The mature seeds serve as a source of high-quality protein and unsaturated fatty acids, notably linoleic acid, which is vital for human nutrition.

**Table 1. Nutritional and Proximate Composition of *Abelmoschus esculentus* Pods**

Parameter	Composition (per 100g fresh weight)
Dietary Fiber	8.16 g
Carbohydrates	4.86 g
Proteins	3.55 g
Total Ash	7.53 %
Fat	0.19 g
Energy	33 kcal
Moisture Content	90.0 - 92.0 %
Acid-Insoluble Ash	0.93 %
Water-Soluble Ash	4.0 %

### 3.2. Polysaccharide Structure and Properties

Okra gum is chemically classified as a complex acidic polysaccharide. Its primary structure consists of a backbone of (1→4)-linked  $\alpha$ -D-galacturonic acid and (1→2)-linked  $\alpha$ -L-rhamnose, with side chains composed of galactose and other neutral sugars [7-10]. The presence of numerous hydroxyl (-OH) groups along the polymer chain facilitates hydrogen bonding, which accounts for its high hygroscopicity and water-retention capacity. The physical state of the purified gum is typically a brownish, odorless, and tasteless powder. Analytical assessments reveal a total ash content of approximately 7.53%, with acid-insoluble ash at 0.93%, indicating a relatively high degree of mineral association within the natural matrix. Surface energy measurements of a 0.25% w/v mucilage solution have yielded values of approximately 0.0405 J/m<sup>2</sup>, suggesting favorable wetting properties for granulation and coating processes.

## 4. Isolation and Purification Techniques

### 4.1. Aqueous Extraction

The extraction of mucilage from *A. esculentus* pods is primarily achieved through aqueous systems, utilizing the natural solubility of its polysaccharides in water. One standardized protocol involves slicing fresh pods and immersing them in distilled water at a

controlled temperature of 60 °C for approximately four hours [11-14]. Continuous agitation during this period maximizes the yield by facilitating the diffusion of the polymer into the solvent. The resulting viscous solution is filtered through multiple layers of muslin cloth to remove fibrous debris [15,16].

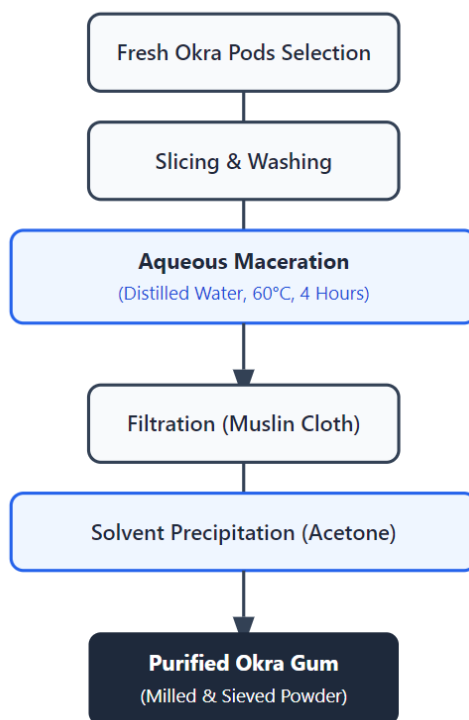


Figure 1. Extraction and Purification of Okra Gum

#### 4.2. Solvent Precipitation

Following filtration, the mucilage is precipitated from the aqueous filtrate using organic solvents, most commonly acetone or ethanol. The choice of solvent and the fruit-to-water ratio significantly influence both the yield and the purity of the final product. Research indicates that maintaining a 1:6 ratio of fruit to water and employing a cold maceration technique at 4–5 °C for 12 hours can preserve the bioactivity and antioxidant properties of the extract, even if the total yield remains comparable to hot extraction methods [17, 18].

#### 4.3. Post-Extraction Processing

Once precipitated, the gum is collected, washed with additional solvent to remove impurities, and dried at temperatures not exceeding 105 °C to prevent thermal degradation. The dried material is then milled into a fine powder and stored in airtight containers. This processed form is evaluated for organoleptic characteristics, including color, odor, and texture, to ensure consistency across different batches [16]

### 5. Physicochemical Characterization of Okra Gum

The performance of *Abelmoschus esculentus* mucilage in industrial applications is governed by its complex physicochemical profile. Systematic evaluation of these parameters is essential to establish quality control standards and predict the behavior of the polymer in diverse matrices.

#### 5.1. Macromolecular Properties

##### 5.1.1. Fractionation and Cultivar Variations

Chromatographic profiling reveals that okra polysaccharides often exist in distinct molecular weight fractions. Research indicates two primary ranges: a high molecular weight fraction ( $2.76 \times 10^3$  to  $4.20 \times 10^3$  kDa) and a lower molecular weight fraction ( $0.11 \times$

$10^3$  to  $0.90 \times 10^3$  kDa) [6]. While the fundamental sugar composition remains consistent across different cultivars, the ratio of these fractions can vary based on genotype, maturity, and environmental growth conditions.

### 5.1.2. Biological Effects of Molecular Weight

The lower molecular weight fractions are often associated with enhanced biological activity. Their smaller size may facilitate improved cellular membrane permeability, potentially increasing the efficacy of the gum in therapeutic roles such as antioxidant or antimicrobial applications [7].

## 5.2. Solubility and Swelling Dynamics

### 5.2.1. Solvency in Polar and Non-Polar Media

The solubility of okra gum is highly dependent on temperature and solvent polarity. In accordance with British Pharmacopoeia standards, the gum exhibits complete solubility in warm water, forming a viscous mucilage, but only slight solubility in cold water [8]. It is essentially insoluble in organic solvents such as benzene, ethanol, acetone, and liquid paraffin, which allows for its isolation via solvent precipitation.

**Table 2. Solubility Profile of Purified Okra Gum in Various Media**

Solvent	Solubility Observations
Warm Water (60°C - 70°C)	Completely soluble; forms viscous mucilage
Cold Water (25°C)	Slightly soluble; limited hydration
Ethanol (95%)	Insoluble; induces precipitation
Acetone	Insoluble; used for purification
Benzene	Insoluble
Liquid Paraffin	Insoluble
Chloroform	Insoluble

### 5.2.2. Swelling Index and Hydration Capacity

The swelling capacity of the gum is a critical indicator of its ability to act as a matrix former. When 1.0 g of the gum is agitated in distilled water, it undergoes rapid hydration, significantly increasing in volume [9]. This high swelling index is attributed to the expansion of the polysaccharide chains as they absorb water into the interstitial spaces of the polymer network, a property vital for controlled-release and gastro-retentive systems.

## 5.3. Thermal Behavior and Stability

### 5.3.1. Thermogravimetric Analysis (TGA)

TGA provides information about the thermal degradation profile of the biopolymer. Analysis typically shows an initial mass loss below 100°C due to the evaporation of adsorbed moisture, followed by a stable plateau. Significant thermal decomposition usually occurs at higher temperatures, confirming that the gum can withstand standard pharmaceutical processing temperatures, such as those used in tablet drying [10].

### 5.3.2. Differential Scanning Calorimetry (DSC)

DSC analysis identifies endothermic and exothermic transitions. An endothermic peak is often observed between 30°C and 100°C, corresponding to the glass transition or dehydration phase. The absence of sharp melting peaks reinforces the amorphous nature of the polysaccharide, which contributes to its film-forming and binding capabilities [11].

## 5.4. Rheological and Flow Properties

### 5.4.1. Viscosity and Concentration Dependencies

Okra mucilage is characterized by high viscosity even at low concentrations. At a 1% w/v concentration, the solution maintains a pH typically between 5.5 and 6.5, which is compatible with many physiological environments [12]. Its rheological behavior is often pseudoplastic (shear-thinning), which is advantageous for liquid formulations that require easy pouring but stability upon standing.

#### 5.4.2. Micromeritic Evaluation

The flowability of the powdered gum is assessed through the angle of repose and density measurements. A low angle of repose (typically  $<30^\circ$ ) indicates good flow properties, which is essential for uniform die filling during high-speed tablet compression. Calculations of bulk and tapped densities allow for the determination of Carr's Index and Hausner ratio, further characterizing the compressibility of the material [13].

**Table 3. Micromeritic and Flow Properties of Dried Okra Gum Powder**

Physical Parameter	Typical Value / Range
Bulk Density	0.55 - 0.62 g/cm <sup>3</sup>
Tapped Density	0.68 - 0.75 g/cm <sup>3</sup>
Angle of Repose ( $\theta$ )	28° - 32° (Good Flow)
Carr's Compressibility Index	15% - 18%
Hausner Ratio	1.15 - 1.22
Surface Energy (0.25% w/v)	0.0405 J/m <sup>2</sup>
pH (1% w/v aqueous solution)	5.5 - 6.5

## 6. Functional Applications in Pharmaceutical Technology

The multifunctional nature of *A. esculentus* mucilage allows it to serve multiple roles in drug delivery, often outperforming synthetic counterparts in terms of safety and cost-effectiveness.

### 6.1. Binding agent

#### 6.1.1. Binding Strength and Mechanical Integrity

In solid oral dosage forms, okra gum acts as a potent binder. Comparative studies at concentrations of 1%, 3%, and 5% show that okra gum provides significantly higher binding strength than pre-gelatinized starch [14]. Tablets formulated with okra gum exhibit hardness values ranging from 7.0 to 8.5 kg/cm<sup>2</sup> and low friability, ensuring they can withstand the mechanical stresses of packaging and transport.

**Table 4. Comparison of Okra Gum vs. Pre-gelatinized Starch**

Binder Type	Concentration (%)	Tablet Hardness (kg/cm <sup>2</sup> )	Friability (%)
Okra Gum	1%	5.2 ± 0.3	0.85
	3%	7.4 ± 0.2	0.42
	5%	8.5 ± 0.4	0.18
Pre-gelatinized Starch	1%	2.5 ± 0.1	1.25
	3%	3.8 ± 0.2	0.95
	5%	4.5 ± 0.3	0.72

#### 6.1.2. Influence on Disintegration and Dissolution

While providing strong structural integrity, the concentration of the gum must be optimized to balance disintegration time. At higher concentrations, the formation of a dense gel matrix can delay the penetration of water, thus slowing the dissolution rate. This makes it an ideal candidate for sustained-release formulations where a gradual release of the API is desired [15].

### 6.2. Application in Gastro-Retentive Systems

#### 6.2.1. Buoyancy and Floating Mechanisms

Okra gum's high swelling capacity and low density upon hydration make it an effective floating agent. In gastro-retentive drug delivery systems (GRDDS), such as those for Metformin hydrochloride, the gum facilitates prolonged gastric residence time [16]. This ensures that the drug is released slowly in the upper gastrointestinal tract, where absorption is most efficient.

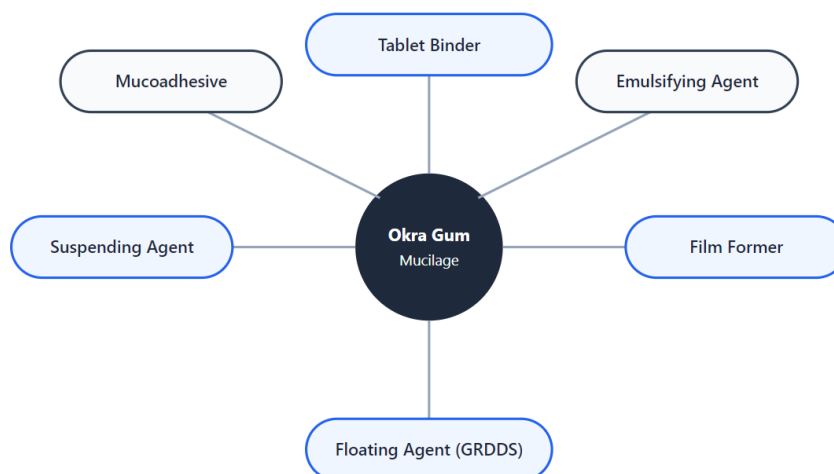


Figure 2. Applications of Okra Gum in Drug Delivery Systems

### 6.2.2. Sustained-Release Kinetics

Okra gum regulates the diffusion of drugs according to specific kinetic models by forming a robust hydrophilic matrix, such as zero-order release. This provides a constant therapeutic effect and minimizes the plasma concentration fluctuations associated with conventional immediate-release tablets

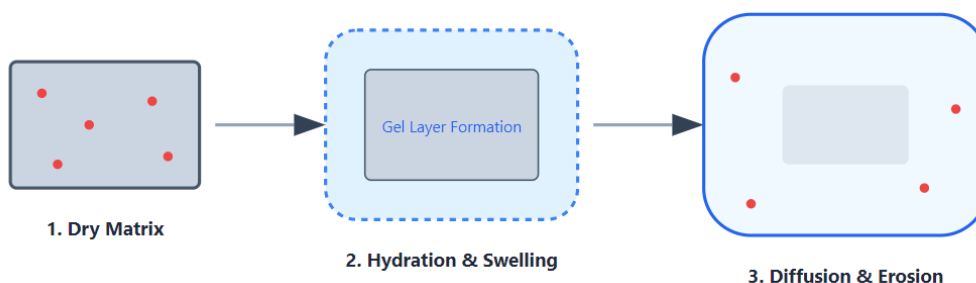


Figure 3. Mechanism of Sustained Drug Release from an Okra-Based Hydrophilic Matrix

## 7. Advanced Pharmaceutical Functionalities

Beyond its role as a primary binder, *Abelmoschus esculentus* mucilage serves several specialized functions that enhance the stability and performance of diverse dosage forms.

### 7.1. Suspending and Stabilizing Properties

#### 7.1.1. Sedimentation and Flocculation Control

In pharmaceutical suspensions, maintaining a uniform dispersion of insoluble particles is essential for dose uniformity. Okra mucilage exhibits superior suspending performance compared to traditional agents like tragacanth and sodium carboxymethyl cellulose (CMC) [17]. At a concentration of 4% w/v, it provides optimal sedimentation volume and prevents the formation of a non-redispersible "cake" by facilitating controlled flocculation.

#### 7.1.2. Rheological Modifier

The pseudoplastic nature of the gum ensures that suspensions remain stable during storage but flow easily upon agitation. This behavior is critical for patient administration, ensuring that the medication can be accurately measured and poured without losing its homogenous distribution [18].

## 7.2. Film-Forming and Coating Applications

### 7.2.1. Barrier Properties and Taste Masking

Okra gum serves as an efficient natural film-coating agent. Its ability to form a flexible, cohesive layer over solid dosage forms makes it suitable for masking unpleasant tastes and odors of certain APIs [19]. When compared to synthetic film-formers, okra-based coatings offer better biodegradability and environmental safety.

### 7.2.2. Synergy with Other Biopolymers

Blending okra mucilage with other biopolymers, such as chitosan or sodium alginate, can modify the permeability and mechanical strength of the film. Such interpenetrating polymer networks (IPN) are being investigated for site-specific delivery in the colon, where the coating must remain intact through the acidic environment of the stomach [20].

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## 8. Applications in Food and Nutraceutical Technology

The high polysaccharide content and bioactive profile of okra gum facilitate its integration into functional foods and health supplements.

### 8.1. Emulsification and Texture Modification

#### 8.1.1. Stabilization of Oil-in-Water Emulsions

Okra mucilage acts as a natural emulsifier by reducing interfacial tension and forming a protective barrier around oil droplets. Studies have demonstrated its efficacy in stabilizing coconut milk-based emulsions, where it prevents phase separation and enhances visual appeal [21]. Its performance often exceeds that of seaweed-based polysaccharides, particularly in neutral pH environments.

#### 8.1.2. Gelling and Viscosity Enhancement

In the food industry, the gum is utilized as a texture modifier in dairy products, sauces, and dressings. Its ability to retain moisture and provide a smooth mouthfeel makes it a valuable additive for low-fat or reduced-calorie food products [22].

### 8.2. Nutraceutical Development

#### 8.2.1. Hypoglycemic and Antidiabetic Potential

Okra-based nutraceuticals are increasingly recognized for their role in glucose metabolism. Formulations utilizing both the pods and seeds have shown significant alpha-glucosidase inhibitory activity *in vitro*, which helps in reducing postprandial blood glucose levels [23].

#### 8.2.2. Antioxidant and Prebiotic Effects

The presence of phenolic compounds and flavonoids within the mucilage matrix contributes to its antioxidant capacity. As a non-digestible carbohydrate, okra gum may serve as a prebiotic, supporting the growth of beneficial gut microbiota and promoting overall gastrointestinal health [24].

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## 9. Therapeutic Activities

### 9.1. Anti-Adhesive Mechanisms against Gastric Pathogens

One of the most notable therapeutic properties of okra gum is its ability to inhibit the adhesion of *Helicobacter pylori* to the human gastric mucosa [25]. The complex rhamnogalacturonan structure of the gum interacts with bacterial surface receptors, preventing colonization and potentially reducing the risk of gastric ulcers and related malignancies.

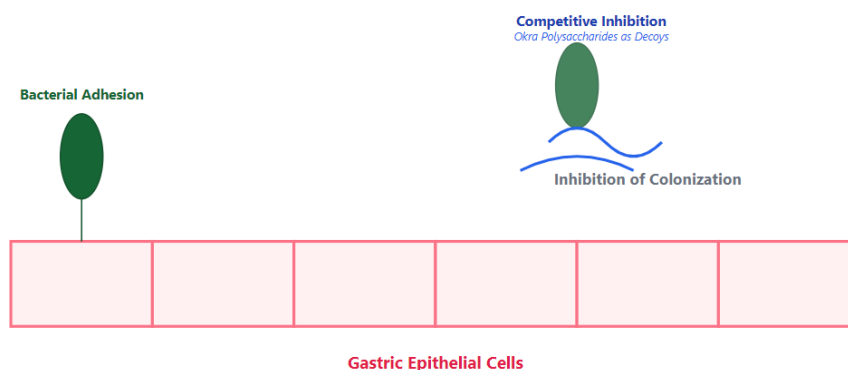


Figure 4. Anti-adhesive Mechanism of Okra Polysaccharides against *H. pylori*

## 9.2. Plasma Volume Expander

Research has explored the potential of purified okra gum fractions as cost-effective plasma expanders. Its high molecular weight and biocompatibility allow it to maintain osmotic pressure within the vascular system, offering a naturally sourced alternative to synthetic colloids [26].

Table 5. Summary of Therapeutic Activities and Biological Mechanisms of Okra Mucilage

Biological Activity	Mechanism of Action	Proposed Application
Anti-adhesive	Inhibition of <i>H. pylori</i> surface receptor binding	Gastric ulcer prevention
Hypoglycemic	Inhibition of $\alpha$ -glucosidase and delayed glucose absorption	Type II Diabetes management
Antioxidant	Scavenging of ROS via phenolic/flavonoid constituents	Anti-aging and cytoprotection
Hypolipidemic	Bile acid sequestration and cholesterol binding	Hyperlipidemia treatment
Mucoadhesive	Hydrogen bonding with mucosal glycoproteins	Site-specific drug delivery
Plasma Expander	Maintenance of oncotic pressure via high MW polymers	Emergency medicine

## 9.3. Wound Healing and Mucoadhesion

The bio-adhesive nature of the mucilage facilitates its use in topical and mucosal drug delivery. The gum prolongs the contact time of therapeutic agents by adhering to biological membranes, which is particularly beneficial in treating oral or vaginal infections and promoting the healing of damaged tissues [27].

## 10. Conclusion

*Abelmoschus esculentus* mucilage due to its complex structural configuration provides a unique set of physicochemical attributes including high swelling capacity, pseudoplastic rheology, and robust mechanical integrity that address modern challenges in drug delivery and food science. As a pharmaceutical excipient, it excels as a binder, rate-retardant matrix, and stabilizing agent, offering a sustainable and non-toxic alternative to synthetic polymers. The biological activities of the gum, ranging from its anti-adhesive effects against gastric pathogens to its hypoglycemic potential, further elevate its status from a simple adjuvant to a functional bioactive component. While its efficacy in controlled-release systems and nutraceutical formulations is well-documented, further research into its molecular fractionation and interaction with diverse APIs will likely broaden its industrial scope. Okra gum stands as a versatile, eco-friendly, and cost-efficient biomaterial poised to significantly impact the future of green pharmaceutical manufacturing and personalized nutrition.

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