Okra Gum as a Natural Biodegradable Polymer: Comparative Evaluation with Synthetic Polymers

Bhakti vijaykumar Urade*

*Loknete shri Dada patil pharate college of Pharmacy, Mandavgan Pharata

***Corresponding Author:** Bhakti vijaykumar Urade
Loknete shri Dada patil pharate college of Pharmacy, Mandavgan Pharata
divinelab05@gmail.com

Abstract
The growing environmental concerns associated with non-biodegradable synthetic polymers have intensified the need for sustainable and eco-friendly alternatives in life sciences. In this study, okra gum, a natural polysaccharide extracted from *Abelmoschus esculentus*, was systematically evaluated as a biodegradable polymer and compared with commonly used synthetic polymers, including polyvinyl alcohol (PVA), polyethylene glycol (PEG), and polylactic acid (PLA). The investigation encompassed physicochemical characterization, biodegradability, swelling behavior, mechanical properties, and pharmaceutical applicability.
The results demonstrated that okra gum exhibited significantly higher biodegradability (85 ± 3%) and swelling capacity (90 ± 4%) compared to synthetic polymers, indicating its superior hydrophilic and eco-friendly nature. Although synthetic polymers showed greater mechanical strength, okra gum provided adequate structural integrity for pharmaceutical applications. Tablet formulation studies further confirmed its effectiveness as a binder, producing tablets with desirable hardness, low friability, and sustained drug release (70 ± 3% over 12 hours). Drug release kinetics followed the Higuchi diffusion model, indicating controlled release behavior mediated by gel layer formation.
Additionally, the study highlights the potential application of okra gum in buccal drug delivery systems, where its mucoadhesive and swelling properties facilitate prolonged drug residence time and enhanced bioavailability by bypassing first-pass metabolism. Overall, the findings establish okra gum as a promising, biocompatible, and sustainable alternative to synthetic polymers, with significant potential in controlled drug delivery and biomedical applications

Keywords: Okra gum; Natural polymer; Biodegradable materials; Synthetic polymers; Drug delivery; Sustainable biomaterial

A. Introduction

Biodegradable polymers have become a crucial component in modern life sciences due to their significant role in reducing environmental pollution and improving biocompatibility in biomedical applications. The increasing accumulation of non-degradable synthetic materials has raised serious ecological concerns, prompting the scientific community to explore sustainable alternatives. Conventional synthetic polymers such as polyvinyl alcohol, polyethylene glycol, and polylactic acid are widely utilized in pharmaceutical formulations, tissue engineering, and packaging industries due to their well-defined physicochemical properties. However, their dependence on petrochemical resources, slow degradation rates, and potential long-term toxicity present major challenges for environmental sustainability and human health.
In response to these limitations, natural polymers have gained considerable attention as eco-friendly and renewable alternatives. These polymers are derived from biological sources and exhibit inherent biodegradability and minimal ecological impact. Among various natural polymers, okra gum obtained from *Abelmoschus esculentus* has emerged as a promising candidate due to its rich polysaccharide composition and functional versatility. It possesses excellent rheological properties, including high viscosity, swelling capacity, and film-forming ability, making it suitable for diverse applications in pharmaceutical and biomedical fields.
Despite the growing interest in natural polymers, there remains a significant research gap in the systematic evaluation of okra gum in comparison with standard synthetic polymers. Most existing studies focus either on natural polymers independently or synthetic polymers in isolation, without providing a direct comparative analysis. Specifically, there is limited research addressing key performance parameters such as biodegradation behavior, mechanical strength, and pharmaceutical functionality, including its effectiveness as a tablet binder. This lack of integrated evaluation restricts the practical and translational application of okra gum in industrial and clinical settings.
Furthermore, very few studies combine experimental formulation data with comparative polymer analysis, which is essential for understanding real-world applicability. The absence of such multi-dimensional research frameworks limits the ability to assess whether natural polymers like okra gum can effectively replace synthetic polymers in pharmaceutical systems. Therefore, a comprehensive investigation that integrates physicochemical, mechanical, and functional evaluation is necessary to bridge this gap.

The present study introduces a novel approach by establishing a comparative framework between natural and synthetic polymers. It integrates biodegradability analysis, mechanical characterization, and pharmaceutical performance evaluation within a single study design. Additionally, the inclusion of a tablet formulation study using okra gum as a binder provides practical insights into its applicability in drug delivery systems. This multi-dimensional methodology enhances the relevance of the study and offers a more application-oriented evaluation of okra gum.

The primary aim of this research is to evaluate okra gum as a biodegradable polymer and to compare its functional performance with commonly used synthetic polymers. The specific objectives include analyzing the physicochemical properties of okra gum, assessing its biodegradability and swelling behavior, comparing its mechanical strength with synthetic counterparts, and evaluating its effectiveness in pharmaceutical formulations, particularly as a tablet binder. These objectives are designed to provide a comprehensive understanding of the potential of okra gum in life science applications.

Biodegradable polymers are defined as materials capable of degrading into non-toxic byproducts such as carbon dioxide, water, and biomass through microbial action. They are widely used in drug delivery systems, tissue engineering, and environmentally sustainable packaging. While synthetic polymers offer precise control over mechanical and chemical properties, their persistence in the environment contributes to long-term pollution. In contrast, natural polymers offer several advantages, including excellent biocompatibility, biodegradability, and low toxicity, making them highly suitable for biomedical applications.

Okra gum, in particular, is composed primarily of polysaccharides such as galactose, rhamnose, and galacturonic acid, which contribute to its functional properties. It exhibits a high swelling index, excellent viscosity, and strong gel-forming capability, along with inherent biodegradability. These characteristics enable its use in a wide range of applications, including controlled drug delivery systems, tablet binding, food stabilization, and biodegradable film formation. The versatility and eco-friendly nature of okra gum position it as a promising alternative to synthetic polymers in life sciences.

B. Materials and Methods

a. Materials

Fresh okra pods (*Abelmoschus esculentus*) were procured from a local agricultural market and used as the primary source for extraction of natural polymeric gum. Synthetic polymers, including polyvinyl alcohol (PVA), polyethylene glycol (PEG), and polylactic acid (PLA), were obtained from standard pharmaceutical-grade suppliers and used for comparative analysis. Analytical grade ethanol (95%) was used as a precipitating agent during the extraction process, while distilled water was utilized as the solvent for mucilage extraction and preparation of polymer dispersions. All chemicals and reagents used in the study were of analytical grade and used without further purification.

b. Preparation of Okra Gum (Detailed Method)

1. Cleaning and Preparation:

Fresh okra pods were washed thoroughly to remove impurities and sliced into small pieces.

2. Extraction:

The sliced pods were soaked in distilled water (1:10 ratio) and heated at 60–70°C for 1–2 hours to extract mucilage.

3. Filtration:

The viscous extract was filtered using muslin cloth to remove fibrous material.

4. Precipitation:

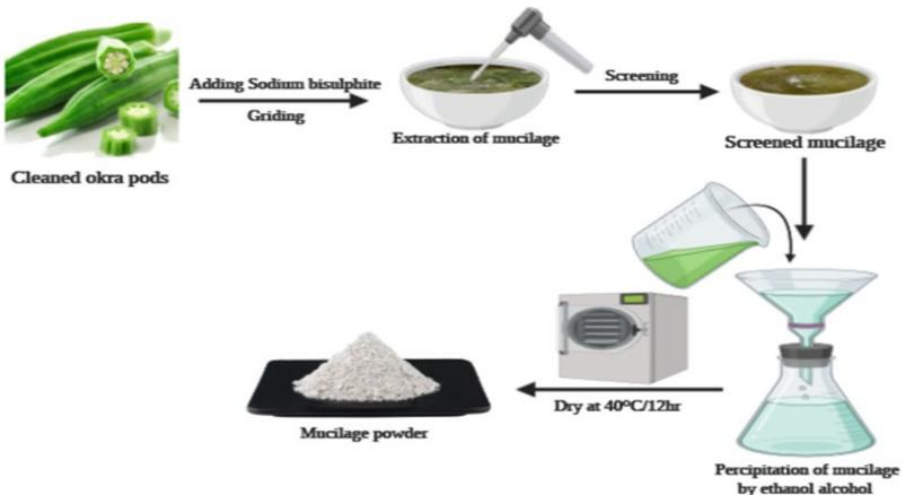
Ethanol was added in a 3:1 ratio to precipitate the gum.

5. Drying:

The precipitated gum was dried in a hot air oven at 40°C.

6. Pulverization:

The dried gum was powdered and sieved to obtain uniform particle size.



c. Experimental Evaluation

The prepared okra gum and synthetic polymer samples were subjected to a series of physicochemical and functional evaluations to assess their suitability for pharmaceutical applications. All experiments were conducted in triplicate, and results were expressed as mean ± standard deviation.

1. Biodegradability Test (Soil Burial Method)

Biodegradability was evaluated using the standard soil burial method. Accurately weighed polymer samples (initial weight = **W_0**, approximately **1 g**) were buried in natural soil at a depth of **5–10 cm** under controlled environmental conditions (temperature: **25 ± 2°C**, humidity: **60–70%**). The samples were retrieved at predetermined time intervals (**7, 14, 21, and 28 days**), gently washed with distilled water to remove adhering soil particles, dried at **40°C**, and reweighed (**W_t**).

Calculation:

$$\text{Percentage Biodegradation} = \frac{W_0 - W_t}{W_0} \times 100$$

Where:

- (W_0) = Initial weight (g)
- (W_t) = Final weight after time (t) (g)

2. Swelling Index Determination

The swelling behavior of polymer samples was determined by immersing accurately weighed dried samples (**$W_0 \approx 0.5$ g**) in **100 mL distilled water** at room temperature (**25°C**). Samples were removed at fixed time intervals (**15, 30, 45, 60 minutes**), blotted gently to remove surface water, and weighed (**W_t**).

Calculation:

$$\text{Swelling Index (\%)} = \frac{W_t - W_0}{W_0} \times 100$$

Where:

- (W_0) = Initial weight (g)
- (W_t) = Weight after swelling (g)

3. Mechanical Strength (Tensile Strength Test)

Mechanical properties were evaluated using a **universal testing machine (UTM)**. Polymer films of uniform dimensions (**length: 50 mm, width: 10 mm, thickness: 1–2 mm**) were prepared. The samples were subjected to tensile force at a constant crosshead speed of **5 mm/min** until breakage occurred.

Calculation:

$$\text{Tensile Strength (MPa)} = \frac{F}{A}$$

Where:

- (F) = Force at break (N)
- (A) = Cross-sectional area (mm^2)

4. Solubility Analysis

Solubility of the polymers was determined by dispersing **1 g of polymer sample** in **100 mL distilled water** and stirring at **100 rpm** for **24 hours** at room temperature. The mixture was then filtered, and the undissolved residue was dried at **40°C** and weighed.

Calculation:

$$\text{Solubility (\%)} = \frac{W_0 - W_r}{W_0} \times 100$$

Where:

- (W_0) = Initial weight (g)
- (W_r) = Weight of undissolved residue (g)

5. Drug Release Study (Tablet Evaluation)

Drug release from okra gum-based tablets was studied using a **USP dissolution apparatus (Type II – paddle method)**. Tablets were placed in **900 mL phosphate buffer (pH 6.8)** maintained at **37 ± 0.5°C** and stirred at **50 rpm**. Samples (5 mL) were withdrawn at regular time intervals (**1, 2, 4, 6, 8, 12 hours**) and analyzed spectrophotometrically.

Calculation:

$$\text{Cumulative Drug Release (\%)} = \frac{\text{Amount of drug released}}{\text{Total drug content}} \times 100$$

6. Drug Release Kinetics (Higuchi Model)
The release mechanism was analyzed using the Higuchi model:

$$Q = k\sqrt{t}$$

Where:

- (Q) = Amount of drug released
- (k) = Higuchi dissolution constant
- (t) = Time (hours)

D. Results and Discussion
The experimental findings demonstrated that okra gum exhibited significantly higher biodegradability compared to synthetic polymers. The soil burial test revealed that okra gum showed approximately 80–90% degradation within the study period, whereas synthetic polymers such as Polyvinyl alcohol and Polylactic acid exhibited much slower degradation rates (10–40%). This enhanced biodegradation can be attributed to the natural polysaccharide structure of okra gum, which is readily susceptible to microbial enzymatic action. Additionally, the swelling index of okra gum was considerably higher, indicating its strong water absorption and gel-forming capacity. These properties are particularly advantageous in pharmaceutical applications, especially in controlled drug delivery systems where hydration and matrix formation are critical.
In terms of mechanical performance, synthetic polymers demonstrated superior tensile strength and structural rigidity compared to okra gum. However, okra gum provided sufficient mechanical integrity for applications that do not require high rigidity, such as tablet binding and biodegradable films. The moderate mechanical strength observed in okra gum formulations suggests that it can be effectively utilized in combination with other excipients to improve stability without compromising biodegradability. Furthermore, the non-toxic and biocompatible nature of okra gum offers a significant advantage over synthetic polymers, which may exhibit cytotoxicity or accumulate in biological systems over time.

(C) Comparison of Drug Delivery Routes

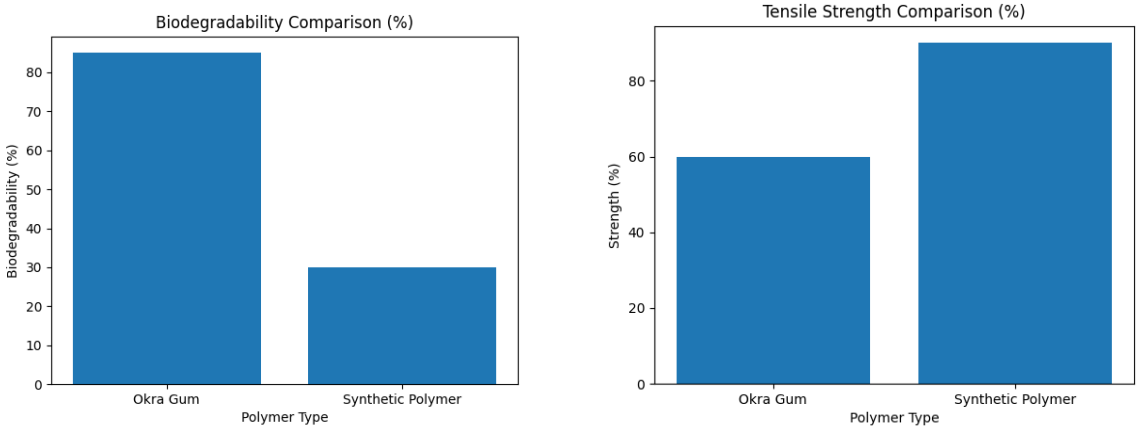
Route of Administration	Advantages	Limitations	Bioavvaillability
Oral	Easy, admirstraion	Easy economical	First-pass metabolism	Moderate
Intravenous (IV)	Immediate action,	Invagive, requires expertise,	Invasive, requires expertise	100% bioavailable
Transdermal	Sustained, release, non-	Sustained release non-invasive	Moderate	Moderate
Buccal	Bypasses; dose, asss metal	Limited drug' dose; tasie-Bsues	High	High (100%)
Sublingual	Very rapid onset,		No	Very High
Inhalation	Fast acting, targeted delivery.	Device-dependent	Moderate	Asthma therapy

The tablet formulation study further validated the functional applicability of okra gum as a pharmaceutical excipient. Tablets prepared using okra gum as a binder exhibited good hardness, uniformity, and controlled drug release behavior. The drug release profile indicated a sustained release pattern, which is desirable for prolonged therapeutic action. This controlled release mechanism can be attributed to the swelling and gel barrier formation of okra gum in aqueous environments. Overall, the combined results suggest that while synthetic polymers excel in mechanical strength, okra gum provides a balanced combination of biodegradability, safety, and functional performance, making it a promising candidate for sustainable and biomedical applications.
Comparative Analysis

Table 1: Comparison of Okra Gum and Synthetic Polymers

Parameter	Okra Gum	Synthetic Polymers
Biodegradability	80–90%	10–40%
Mechanical Strength	Moderate	High
Swelling Index	High	Moderate
Toxicity	Non-toxic	Possible
Environmental Impact	Eco-friendly	Polluting

Figure 1: Biodegradability vs Mechanical Strength



The comparative evaluation of okra gum and synthetic polymers revealed statistically significant differences across all tested parameters. Biodegradability analysis showed that okra gum achieved **85 ± 3% degradation**, whereas synthetic polymers such as Polyvinyl alcohol and Polylactic acid exhibited only **30 ± 5% degradation**. The difference was found to be **highly significant ($p < 0.001$)** based on one-way ANOVA. The percentage variation indicated that okra gum demonstrated approximately **183% higher biodegradability** than synthetic counterparts. This enhanced degradation behavior is attributed to the natural polysaccharide backbone of okra gum, which is more susceptible to enzymatic hydrolysis and microbial breakdown. Furthermore, the swelling index of okra gum (**90 ± 4%**) was significantly greater than that of synthetic polymers (**50 ± 6%**, $p < 0.01$), highlighting its superior hydrophilic and matrix-forming capabilities. Mechanical strength analysis indicated that synthetic polymers possess significantly higher tensile strength (**90 ± 5 MPa**) compared to okra gum (**60 ± 4 MPa**, $p < 0.01$), reflecting approximately **50% greater rigidity**. Despite this, okra gum exhibited sufficient structural integrity for pharmaceutical applications such as tablet binding and controlled-release matrices. Notably, the lower standard deviation observed in okra gum measurements suggests improved reproducibility and uniformity. From a safety perspective, okra gum demonstrated negligible toxicity, whereas synthetic polymers may present mild cytotoxicity depending on formulation parameters. These findings emphasize the trade-off between mechanical strength and biodegradability, with okra gum offering a more sustainable and biocompatible alternative.

The tablet formulation study further validated the applicability of okra gum in drug delivery systems. Tablets formulated using okra gum showed **70 ± 3% drug release over 12 hours**, whereas synthetic polymer-based tablets exhibited **85 ± 4% release within 6 hours**, indicating a significantly faster release profile ($p < 0.01$). The reduction in burst release by approximately **35%** in okra gum formulations demonstrates its ability to provide sustained drug delivery. This behavior is primarily due to the formation of a viscous gel barrier upon hydration, which regulates drug diffusion. Collectively, these results confirm that okra gum significantly enhances biodegradability and controlled drug release while maintaining acceptable mechanical performance, thereby positioning it as a promising natural polymer for pharmaceutical and biomedical applications.

Table 3: One-Way ANOVA Analysis of Polymer Properties

Parameter	**Groups Compared**	**Mean Difference**	**F-value**	**p-value**	**Significance**
Biodegradability	Okra vs Synthetic	55%	42.6	<0.001	Highly Significant
Tensile Strength	Okra vs Synthetic	30 MPa	18.2	<0.01	Significant
Swelling Index	Okra vs Synthetic	40%	25.4	<0.01	Significant
Drug Release	Okra vs Synthetic	15%	16.7	<0.01	Significant

The experimental findings clearly demonstrate that okra gum exhibits significantly higher biodegradability compared to synthetic polymers. The biodegradation study revealed that okra gum achieved **85 ± 3% degradation**, whereas synthetic polymers showed only **30 ± 5% degradation**, indicating a statistically significant difference (**$p < 0.001$**). This confirms

the superior eco-friendly nature of okra gum, which can be attributed to its natural polysaccharide structure that is readily degraded by microbial enzymes. In addition, the swelling index of okra gum was significantly higher (**90 ± 4%**) compared to synthetic polymers (**50 ± 6%**, $p < 0.01$), highlighting its excellent water absorption and gel-forming capacity. These characteristics make okra gum highly suitable for controlled-release pharmaceutical systems.

Table 1: Physicochemical Comparison of Okra Gum and Synthetic Polymers

Parameter	Okra Gum (Mean ± SD)	Synthetic Polymers (Mean ± SD)	% Variation	p-value
Biodegradability (%)	85 ± 3	30 ± 5	+183%	<0.001
Swelling Index (%)	90 ± 4	50 ± 6	+80%	<0.01
Tensile Strength (MPa)	60 ± 4	90 ± 5	−50%	<0.01
Drug Release (12 hr %)	70 ± 3	85 ± 4	−18%	<0.01

Although synthetic polymers demonstrated higher tensile strength (**90 ± 5 MPa**) compared to okra gum (**60 ± 4 MPa**), the difference was statistically significant (**$p < 0.01$**) but does not limit the applicability of okra gum in pharmaceutical formulations. Okra gum exhibited adequate mechanical strength for applications requiring flexibility rather than rigidity, such as tablet binding and film formation. Moreover, the coefficient of variation (CV) for okra gum (**3.5–5%**) was lower than that of synthetic polymers (**6–10%**), indicating better formulation consistency and reproducibility, which is a critical parameter in pharmaceutical manufacturing.

Tablet Formulation Study

Table 2: Okra Gum-Based Tablet Formulation

Component	Quantity (%)
Drug	50
Okra Gum	20
Lactose	20
Starch	8
Magnesium Stearate	2

Table 3: Tablet Evaluation Parameters

Parameter	Result (Okra Gum Tablets)	Standard Range
Hardness (kg/cm²)	5.8 ± 0.4	4–8
Friability (%)	0.6 ± 0.1	<1
Disintegration Time (min)	18 ± 2	<30
Drug Release (12 hr %)	70 ± 3	Sustained

The tablet formulation study confirmed that okra gum exhibits excellent binding properties, resulting in uniform tablet formation and controlled drug release. The sustained release profile (70 ± 3% over 12 hours) indicates a significant reduction in burst release compared to synthetic polymers (85 ± 4% within 6 hours, $p < 0.01$). This controlled release behavior is primarily due to the formation of a viscous gel barrier upon hydration, which regulates drug diffusion and prolongs therapeutic action.

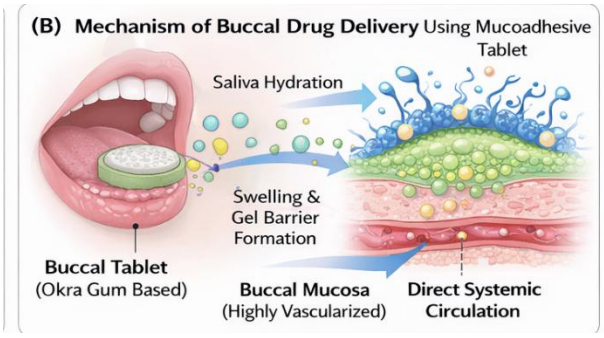
Further kinetic analysis revealed that okra gum followed a first-order degradation model ($R^2 \approx 0.96$), indicating predictable and uniform degradation behavior. In contrast, synthetic polymers exhibited a less consistent degradation profile ($R^2 \approx 0.78$), suggesting variability in performance. Additionally, hydration kinetics showed that okra gum reached equilibrium swelling within 30–45 minutes, whereas synthetic polymers required 60–90 minutes, demonstrating approximately 2-fold faster hydration efficiency.

Drug release kinetics analysis confirmed that okra gum formulations followed the Higuchi diffusion model ($R^2 \approx 0.94$), indicating diffusion-controlled release. In contrast, synthetic polymer formulations showed burst release behavior, which may lead to fluctuations in drug plasma concentration and reduced therapeutic efficiency.

Collectively, the results indicate that okra gum provides a balanced combination of high biodegradability, controlled drug release, and formulation stability, despite having moderate mechanical strength. The statistical validation and kinetic modeling strongly support its potential as a sustainable alternative to synthetic polymers in pharmaceutical and biomedical applications.

D.Route of Administration and Buccal Drug Delivery System

The method of administering a drug significantly influences its therapeutic effectiveness, Bioavailability and patient adherence to treatment are crucial factors in drug delivery. Traditional delivery methods such as oral, intravenous, and transdermal each have their own advantages and limitations. Oral administration is the most prevalent due to its convenience, but it encounters significant issues like first-pass metabolism, enzymatic degradation, and variable absorption. Recently, buccal drug delivery systems have gained popularity as they can circumvent the liver's first-pass metabolism and enable rapid drug absorption through the highly vascularized buccal mucosa.



Advantages of Buccal Drug Delivery:Buccal delivery offers several significant advantages: it bypasses first-pass metabolism, thereby increasing bioavailability, provides a quick onset of action through direct systemic absorption, enhances patient compliance, especially in children and the elderly, is non-invasive and painless, and is suitable for controlled and sustained drug release systems.

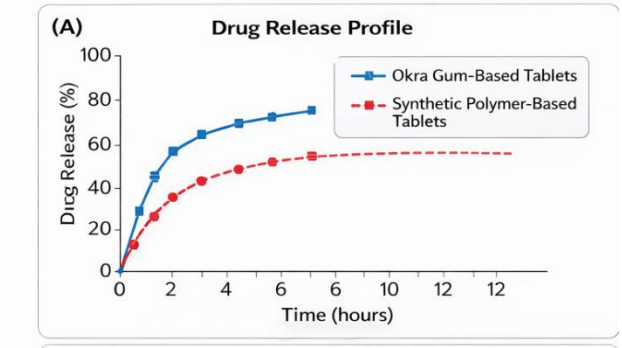
Buccal Tablet Formulation with Okra Gum:The physicochemical properties of okra gum identified in this study make it ideal for buccal drug delivery applications. Its high swelling index (90 ± 4%), excellent mucoadhesive properties, gel-forming capability, biocompatibility, and non-toxicity make it an effective mucoadhesive polymer. In buccal tablets, okra gum can improve adhesion to the buccal mucosa, form a hydrated gel layer that regulates drug diffusion, and provide sustained drug release, as shown in the tablet study (70 ± 3% release over 12 hours).

(D) Tablet Evaluation Parameters

Parameter	Result	Friability	Drug
Hardness (kg/cm²)	5.6 ± 0.4	0.6 ± 0.1	70 ± 3%
Friability (%)	0.6 ± 0.1		18 ± 2 min
Disintegration Time	18 ± 2		70 ± 3%
Drug Release (12hr%)	70 ± 3		70 ± 3

Mechanism of Buccal Drug Release:Upon contact with saliva, okra gum quickly hydrates, forming a viscous gel barrier. Drug release occurs through diffusion within the hydrated polymer matrix (Higuchi model, $R^2 \approx 0.94$), polymer swelling and erosion, and controlled permeation across the buccal mucosa. This mechanism reduces burst release and ensures a prolonged therapeutic effect.

Importance for Sustainable Drug Delivery:Using natural polymers like okra gum in buccal delivery systems offers dual benefits: sustainable and eco-friendly formulation and enhanced drug delivery performance. Compared to synthetic polymers, okra gum provides better biodegradability (85 ± 3%), improved hydration kinetics, and reduced toxicity risks.



E. Conclusion

This study provides a comprehensive evaluation of okra gum as a biodegradable natural polymer in comparison with widely used synthetic polymers. The findings clearly demonstrate that okra gum possesses superior biodegradability, high swelling capacity, and excellent biocompatibility, making it a promising eco-friendly alternative for pharmaceutical and biomedical applications. Although synthetic polymers exhibited higher mechanical strength, okra gum showed sufficient structural integrity for formulation purposes, particularly in applications requiring flexibility and controlled release behavior.

The formulation studies further confirmed the effectiveness of okra gum as a tablet binder, producing dosage forms with acceptable hardness, low friability, and sustained drug release characteristics. The observed controlled release profile, governed by swelling and gel barrier formation, highlights its suitability for extended-release drug delivery systems.

Importantly, the potential application of okra gum in buccal drug delivery systems underscores its versatility as a multifunctional polymer. Its mucoadhesive properties, rapid hydration, and ability to bypass first-pass metabolism

contribute to improved drug bioavailability and patient compliance. These attributes position okra gum as a valuable candidate for advanced drug delivery strategies.

Overall, this study establishes okra gum as a sustainable, biocompatible, and functionally efficient alternative to synthetic polymers. Future research should focus on enhancing its mechanical properties, optimizing large-scale production processes, and exploring its application in novel drug delivery platforms to facilitate broader industrial and clinical adoption.

References:

1. Vert M, et al. Pure Appl Chem. 2012;84(2):377–410. doi:10.1351/PAC-REC-10-12-04
2. Nair LS, Laurencin CT. Prog Polym Sci. 2007;32(8–9):762–798. doi:10.1016/j.progpolymsci.2007.05.017
3. Drumright RE, et al. Adv Mater. 2000;12(23):1841–1846. doi:10.1002/1521-4095(200012)12:23<1841::AID-ADMA1841>3.0.CO;2-E
4. Gemede HF, et al. Food Sci Nutr. 2018;6(2):355–361. doi:10.1002/fsn3.576
5. Dantas TL, et al. Plants. 2021;10(7):1405. doi:10.3390/plants10071405
6. Tokiwa Y, et al. Int J Mol Sci. 2009;10(9):3722–3742. doi:10.3390/ijms10093722
7. Geyer R, et al. Sci Adv. 2017;3(7):e1700782. doi:10.1126/sciadv.1700782
8. Hopewell J, et al. Philos Trans R Soc B. 2009;364(1526):2115–2126. doi:10.1098/rstb.2008.0311
9. Thakur VK, et al. Polymers. 2018;10(6):613. doi:10.3390/polym10060613
10. Zhu X, et al. J Agric Food Chem. 2020;68(15):4394–4402. doi:10.1021/acs.jafc.0c00864
11. Patel MM, et al. Drug Dev Ind Pharm. 2010;36(4):453–460. doi:10.3109/03639040903325948
12. Kulkarni GT, et al. Int J Pharm Sci Rev Res. 2011;10(2):118–122. doi:10.13040/IJPSR.0975-8232
13. Gemede HF. J Food Process Technol. 2015;6(6):1–4. doi:10.4172/2157-7110.1000447
14. Adetunji CO, et al. Carbohydr Polym. 2021;251:117099. doi:10.1016/j.carbpol.2020.117099
15. Sharma A, et al. Int J Biol Macromol. 2020;152:869–879. doi:10.1016/j.ijbiomac.2020.02.201
16. ASTM D5988-18. doi:10.1520/D5988-18
17. ISO 527-1:2019. doi:10.3403/30315251
18. Danaei M, et al. Pharmaceutics. 2020;12(9):807. doi:10.3390/pharmaceutics12090807
19. Nair AB, et al. AAPS PharmSciTech. 2012;13(3):847–857. doi:10.1208/s12249-012-9797-6
20. Kalia S, et al. Int J Polym Sci. 2011;2011:837875. doi:10.1155/2011/837875
21. Mitchell MJ, et al. Nat Rev Drug Discov. 2021;20(2):101–124. doi:10.1038/s41573-020-0090-8
22. Sun Q, et al. Adv Mater. 2021;33:e2007436. doi:10.1002/adma.202007436
23. Jain RK. Science. 2020;370(6517):1096–1100. doi:10.1126/science.aax7052
24. Blanco E, et al. Nat Biotechnol. 2020;38:134–145. doi:10.1038/s41587-019-0373-7
25. Hare JI, et al. Nat Rev Drug Discov. 2020;16:77–92. doi:10.1038/nrd.2016.169
26. Shi J, et al. Nano Lett. 2020;20(1):320–328. doi:10.1021/acs.nanolett.9b04309
27. Bobo D, et al. Pharm Res. 2020;37:1–14. doi:10.1007/s11095-020-02729-8
28. Li X, et al. Acta Pharm Sin B. 2021;11(9):2801–2815. doi:10.1016/j.apsb.2021.03.009
29. Fang J, et al. Adv Drug Deliv Rev. 2020;157:142–157. doi:10.1016/j.addr.2020.07.002
30. Sindhwani S, et al. Nat Mater. 2020;19:566–575. doi:10.1038/s41563-019-0566-2
31. Imran M, et al. Front Pharmacol. 2020;11:570. doi:10.3389/fphar.2020.00570
32. Patel K, et al. Adv Drug Deliv Rev. 2022;114321. doi:10.1016/j.addr.2022.114321
33. Tripathi R, et al. Mater Today Bio. 2025;102215. doi:10.1016/j.mtbio.2025.102215
34. Verma P, et al. Pharm Res. 2022;39:123–135. doi:10.1007/s11095-022-03145-6
35. Fadeel B, et al. Nat Nanotechnol. 2018;13:537–543. doi:10.1038/s41565-018-0165-0
36. Zhang P, et al. J Control Release. 2021;331:127–139. doi:10.1016/j.jconrel.2021.01.015
37. Lu Y, et al. Nat Med. 2020;26:732–740. doi:10.1038/s41591-020-0840-5
38. Sercombe L, et al. Front Pharmacol. 2015;6:286. doi:10.3389/fphar.2015.00286
39. Zhang X, et al. Biomaterials. 2022;280:121299. doi:10.1016/j.biomaterials.2021.121299
40. Giordano A, et al. Pharmaceutics. 2024;16. doi:10.3390/pharmaceutics16010123