Research Article

Development of A Biodegradable Dual-Layer Edible Bilayer Film (Hydrophilic–Hydrophobic Packaging Film) — "PODIBLE" — For Food Packaging Applications

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Abstract

The widespread use of non-biodegradable plastic sachets in instant food products has created acute environmental challenges, with India generating approximately 3.5 million tonnes of plastic waste annually (CPCB, 2022). This study developed and characterised PODIBLE — a biodegradable dual-layer edible bilayer film comprising a hydrophilic inner layer (corn starch + glycerine) and a hydrophobic outer layer (corn starch + beeswax + GMS) — as a functional alternative to single-use plastic seasoning sachets. Formulation optimisation through nine inner-layer trials and four outer-layer trials identified Trial 9 and Trial 4, respectively, as the optimal formulations. The inner film exhibited complete dissolution in hot water (95°C) within 60 seconds with no solid residue. The PODIBLE dual-layer sachet reduced moisture gain from 12.5% (inner film alone) to 4.2%, representing a 66.4% improvement in moisture barrier performance. Water vapour transmission rate (WVTR) was 1850 ± 50 g/m²/day for the inner film and 720 ± 35 g/m²/day for the outer film (61.1% reduction). Tensile strength was 18.2 ± 1.1 MPa (outer) and 12.5 ± 0.8 MPa (inner). Sensory evaluation (n = 10) yielded an overall acceptability score of 8.1/9 on a 9-point hedonic scale. Microbiological analysis confirmed FSSAI compliance with TPC < 10^2 CFU/g and complete absence of E. coli and Salmonella. Biodegradability testing demonstrated ~95% weight loss within 14 days under soil burial conditions. A preliminary shelf-life study confirmed product stability for 75 days under ambient storage. Raw material cost was estimated at less than ₹1.00 per sachet. The novelty of PODIBLE has been recognised through an Ordinary Patent Application filed with the Patent Office of India (Application No. 202641030135, dated 13 March 2026). The findings establish a scientifically sound basis for the commercial scale- up of PODIBLE as a next-generation sustainable food packaging technology.

Keywords: Edible film, dual-layer sachet, biodegradable packaging, starch-based film, beeswax, moisture barrier, WVTR, instant seasoning, PODIBLE.

1. Introduction

Food packaging plays a central role in preserving the quality, safety, and shelf life of food products throughout the supply chain. In the instant and convenience food sector, small plastic sachets are extensively used for packaging seasonings, spices, condiments, and additives (Marsh and Bugusu, 2007). While these sachets offer effective protection against moisture, oxygen, and microbial contamination, they are predominantly manufactured from non-biodegradable synthetic plastics, contributing significantly to environmental pollution and solid waste accumulation. Globally, over 380 million tonnes of plastic are produced annually, a substantial fraction comprising single-use food packaging materials (Han, 2014). Conventional plastic materials such as polyethylene and polypropylene persist in the environment for hundreds of years, posing severe risks to terrestrial and aquatic ecosystems.

In India, the Plastic Waste Management Rules (2016, amended 2021) have accelerated demand for biodegradable alternatives. According to the Central Pollution Control Board (CPCB, 2022), India generates approximately 3.5 million tonnes of plastic waste annually, a significant proportion originating from single-use food packaging. Biopolymer-based edible films prepared from starch, proteins, and lipids have demonstrated potential as sustainable food packaging alternatives (Sothornvit and Krochta, 2005). Among biopolymers, corn starch has emerged as a preferred film-forming material owing to its abundance, low cost, biodegradability, and excellent film-forming characteristics (Aisyah, 2017). However, the inherently hydrophilic nature of starch-based films limits their application in moisture-sensitive packaging contexts. Incorporation of hydrophobic components such as beeswax into the starch matrix has been demonstrated to significantly enhance moisture barrier performance by reducing water vapour permeability (Gutiérrez, 2015). A dual-layer approach — combining a hydrophilic inner layer for dissolution and a hydrophobic outer layer for moisture protection — represents the most effective strategy for addressing this challenge (Velickova et al., 2015; Nyam et al., 2025). Cheng et al. (2024) demonstrated the industrial scalability of starch–beeswax composite films, confirming commercial viability. Ruggeri et al. (2020) further established the effectiveness of layered biopolymer systems in retarding moisture loss and microbial spoilage. The present study aimed to develop PODIBLE (Biodegradable Dual-Layer Edible Bilayer Film — Pods + edible), a complete, consumer-ready dual-layer edible sachet specifically designed for instant food seasoning applications, combining a rapidly soluble inner layer with a moisture-resistant outer layer at a raw material cost below ₹1.00 per sachet — economically competitive with conventional plastic sachets in the Indian market. The specific objectives of the study were to: (i) prepare and optimise an inner edible film using corn starch and glycerine with rapid hot-water solubility; (ii) develop and optimise an outer protective layer using corn starch, beeswax, and GMS with improved moisture barrier performance; (iii) construct a functional dual-layer edible sachet (PODIBLE) for instant seasoning powder packaging; (iv) evaluate physical, functional, mechanical, microbiological, sensory, biodegradability, and shelf-life properties of the developed system; and (v) assess the economic viability of the PODIBLE technology.

2. Materials and Methods

2.1 Materials

All materials used in this study were of food grade, sourced from authorised food ingredient suppliers in Coimbatore, Tamil Nadu, and complied with FSSAI regulations for food contact applications. Corn starch (food grade) was used as the primary film-forming biopolymer; glycerine (99.5% purity, food grade) served as the plasticiser; refined food-grade beeswax provided the hydrophobic moisture barrier; Glycerol Monostearate (GMS, FSSAI-approved) functioned as the emulsifier for beeswax dispersion; and distilled (laboratory grade) water served as the solvent. Commercially available instant seasoning powder was used as the model fill material for sachet construction and evaluation.

2.2 Experimental Design

The experimental work was carried out in three phases: (i) optimisation of the inner layer film formulation through nine systematic trials evaluating different combinations of film-forming agents, plasticisers, and drying conditions; (ii) optimisation of the outer layer film formulation through four systematic trials; and (iii) construction and comprehensive evaluation of the dual-layer PODIBLE sachet using the optimised formulations.

2.3 Inner Layer Film Development

The inner layer was designed to be hydrophilic, with rapid solubility in hot water to allow direct consumption of the seasoning without manual sachet removal. Nine trials were conducted varying film-forming agents (corn starch, gelatine, agar), plasticisers (glycerine, lecithin, GMS), and drying conditions (oven vs room temperature; 24 vs 48 hours). The optimised inner layer preparation protocol (Trial 9) was as follows: 5 g corn starch was dispersed in 100 ml distilled water; 1 ml glycerine was added and the mixture was heated at 70–80°C with continuous magnetic stirring for 15–20 minutes until a uniform, clear, viscous gelatinised solution was obtained; the solution was degassed at 50–55°C for 10 minutes; poured uniformly onto clean glass casting plates; and dried at room temperature (25–28°C) for 48 hours. The dried film was carefully peeled and stored in a sealed container.

Table 1. Inner layer film trial formulations and results (✓ = selected optimised formulation)

Trial	Ingredients	Drying Method	Outcome	Remarks
Trial 1	Agar, GMS, Gelatine, Corn starch, Water	Oven 45–50°C, 4–5 hr	Agar not dissolved; lumps formed; film did not dry	Rejected — poor film formation
Trial 2	Agar, GMS, Gelatine, Corn starch, Water	Oven 55– 60°C + Incubator 30–40°C	Outer surface dried; GMS not dissolved; inner surface moist	Rejected — non-uniform drying
Trial 3	Corn starch, Lecithin, Glycerine, Water	Oven 65–70°C, 4–5 hr	Non-uniform film; white dots; weak structure	Rejected — poor uniformity
Trial 4	Corn starch, Glycerine, Lecithin, Water	Room temp, 24 hr	White and yellow patches; flexible; slightly transparent	Rejected — uneven colour
Trial 5	Gelatine, Glycerine, Water	Oven 65–70°C, 4–5 hr	Over-dried; stuck to casting plate; transparent	Rejected — adhesion problem
Trial 6	Gelatine, Glycerine, Water	Room temp, 24 hr	Transparent, elastic film; dissolved in hot water	Partial — moisture sensitive
Trial 7	Gelatine, Glycerine, Water	Room temp, 48 hr	Slightly shrunken; cling wrap-like texture	Rejected — dimensional instability
Trial 8	Corn starch, Glycerine, Water	Room temp, 24 hr	Transparent, flexible; small pinholes developed during drying	Partial — pinhole defects
Trial 9 ✓	**Corn starch, Glycerine, Water**	**Room temp, 48 hr**	**Transparent, flexible; easily peeled; dissolved in 60 sec**	**SELECTED ✓ — Best performance**

2.4 Outer Layer Film Development

The outer layer was designed to be hydrophobic, providing a moisture barrier to protect the inner layer and seasoning contents during storage. Four trials were conducted. The optimised outer layer preparation protocol (Trial 4) was: 5 g corn starch was dispersed in 100 ml distilled water; 1 ml glycerine was added and the mixture was gelatinised at 70–80°C; 2 g beeswax was separately melted at 70°C in a water bath; 0.5% w/v GMS was dissolved in the hot gelatinised starch–glycerine solution; molten beeswax was slowly poured into the hot starch–GMS solution with continuous vigorous stirring to form a stable emulsion; and the emulsion was cast on glass plates and dried at room temperature for 48 hours.

Table 2. Outer layer film trial formulations and results (✓ = selected optimized formulation)

Trial	Ingredients	Drying Method	Outcome	Remarks
Trial 1	Beeswax, Gelatine, Corn starch, Water	Room temp, 24 hr	Non-uniform drying; uneven texture	Rejected — poor uniformity

Trial 2	Beeswax, GMS, Gelatine, Corn starch, Water	Room temp, 24 hr	White particles; incomplete mixing; moderate flexibility	Partial — incomplete emulsion
Trial 3	Beeswax, Corn starch, Water	Room temp, 48 hr	Phase separation; smooth top, rough bottom; brittle	Rejected — phase separation
Trial 4 ✓	**Beeswax, GMS, Corn starch, Glycerine, Water**	**Room temp, 48 hr**	**Uniform, flexible, slightly transparent; stable film formed**	**SELECTED ✓ — Best performance**

2.5 Dual-Layer Sachet Construction

Dried film sheets were cut into 8 cm × 8 cm pieces. The bilayer sachet was assembled in a sandwich configuration with the inner film (hydrophilic) facing inward and the outer film (hydrophobic) on the exterior. Three edges were heat-sealed using a laboratory impulse heat sealer at 120–130°C and 2–3 kg/cm² for 2–3 seconds; 3.0 g instant seasoning powder was filled; and the top edge was sealed to form a closed, four-edged sachet. A quality inspection was performed on each sachet before use in analytical evaluation.

2.6 Analytical Methods

Film thickness was measured at five randomly selected points per film sample using a digital Vernier calliper (±0.01 mm). Solubility of the inner film in hot water was determined by immersing a 2 cm × 2 cm film sample in 100 ml distilled water at 95°C and recording the time to complete dissolution. Moisture barrier analysis was performed gravimetrically by exposing pre-weighed film samples to 85% RH and 30°C for 24 hours and calculating percentage moisture gain. Water Vapour Transmission Rate (WVTR) was determined using the gravimetric cup method per ASTM E96/E96M at 38°C, 90% RH. Tensile strength (TS) and elongation at break (EAB) were determined per ASTM D882 using a Universal Testing Machine (UTM) on 25 × 100 mm strips at 50 mm/min crosshead speed. Sensory evaluation was conducted by a semi-trained panel of 10 members using a 9-point hedonic scale for appearance, texture, taste, and overall acceptability. Microbiological safety was assessed following FSSAI standard methods for Total Plate Count (TPC), Yeast and Mould, E. coli, and Salmonella. Biodegradability was evaluated using the soil burial method (5 × 5 cm samples in moist garden soil at 25–28°C), with weight loss measured at Days 0, 3, 5, 7, 10, and 14. Shelf-life assessment was conducted by storing sealed PODIBLE sachets at ambient conditions (25–28°C, 55–65% RH) for 75 days with observation at Days 0, 7, 14, 30, 45, 60, and 75. All quantitative experiments were conducted in triplicate (n=3) and data expressed as mean ± standard deviation (SD). Statistical significance of differences between inner and outer film parameters was evaluated using a two-sample t-test at 95% confidence level ($p < 0.05$).

3. Results and Discussion

3.1 Optimisation of Inner and Outer Layer Film Formulations

Nine systematic trials were conducted to optimise the inner layer formulation. Trial 9 — corn starch and glycerine dried at room temperature for 48 hours — was selected as the optimised inner layer formulation (Table 1). The extended 48-hour drying period eliminated the pinhole defects observed in Trial 8 (24 hours), confirming that sufficient drying time is critical for film integrity. Corn starch provided excellent film-forming ability consistent with the findings of Aisyah (2017), while glycerine acted as an effective plasticiser, preventing brittleness. Gelatine- based trials (Trials 5–7) were eliminated due to adhesion issues (Trial 5), moisture sensitivity (Trial 6), and dimensional instability — cling-wrap-like shrinkage during extended drying (Trial 7) — consistent with the known physical ageing behaviour of gelatine films reported by Jridi et al. (2020). Four trials optimised the outer layer formulation. Trial 4 — corn starch, beeswax, GMS, and glycerine dried for 48 hours — was selected (Table 2). Trials 1 and 3, lacking GMS, demonstrated phase separation of beeswax from the aqueous starch matrix, resulting in non-uniform films. GMS, as an amphiphilic emulsifier, reduced interfacial tension between the molten beeswax and the aqueous starch phase, facilitating the formation of a stable, homogeneous film-forming emulsion — consistent with the

mechanisms reported by Sothornvit and Krochta (2005). Trial 2 showed incomplete emulsion due to gelatine interfering with emulsification.

3.2 Physical Properties of Optimised Films

The inner film exhibited lower thickness (0.28 ± 0.02 mm) compared to the outer film (0.35 ± 0.03 mm), attributed to the increased total solid content from beeswax incorporation is shown in table 3 presents the physical properties of the optimised inner (Trial 9) and outer (Trial 4) films. The transparency of the inner film is characteristic of corn starch–glycerine films, while the slight opacity of the outer film results from crystalline beeswax particles dispersed within the starch matrix — consistent with Pérez-Vergara et al. (2020) for cassava starch–beeswax films.

Table 3. Physical properties of optimised PODIBLE inner and outer films

Property	Inner Film (Trial 9)	Outer Film (Trial 4)
Thickness (mm)	0.28 ± 0.02	0.35 ± 0.03
Appearance	Transparent	Slightly opaque
Flexibility	High	Moderate
Surface texture	Smooth, uniform	Smooth, slightly waxy
Colour	Colourless	Pale yellow-white
Peelability from plate	Easy	Easy

3.3 Solubility Analysis

Solubility results are presented in Table 4. The inner film demonstrated complete dissolution in hot water at 95°C within approximately 60 seconds, with no solid residue and a clear, homogeneous dispersion. This rapid dissolution is attributed to the hydrophilic nature of corn starch, which readily absorbs water, swells, and disintegrates at elevated temperatures, consistent with Kramer (2009). The complete absence of solid residue confirms the edibility of the inner film — an essential requirement for a packaging material intended for consumption with the food product.

Table 4. Solubility analysis results for the optimised inner film (Trial 9)

Parameter	Result
Water temperature	95°C
Dissolution time	~60 seconds
Residue after dissolution	None observed

Visual appearance during dissolution	Clear, homogeneous dispersion

3.4 Moisture Barrier Analysis

Moisture barrier performance results are presented in Table 5. Incorporation of the beeswax-containing outer layer significantly reduced moisture gain from 12.5% (inner film alone) to 4.2% (PODIBLE dual-layer sachet), representing a 66.4% improvement in moisture barrier performance. The hydrophobic beeswax component creates an effective barrier against water vapour diffusion by generating a tortuous path for water molecule migration through the film matrix, consistent with Gutiérrez (2015). This improved moisture resistance ensures the seasoning powder remains free-flowing and protected from caking during ambient storage.

Table 5. Moisture barrier analysis — inner film vs PODIBLE dual-layer sachet (85% RH, 30°C, 24 h)

Sample	Initial Weight (g)	Final Weight (g)	Moisture Gain (%)
Inner film only (no outer layer)	1.00	1.125	12.5%
PODIBLE dual-layer (with outer layer)	1.00	1.042	4.2%

3.5 Sensory Evaluation

Sensory scores are presented in Table 6. The PODIBLE sachet received high scores across all attributes, with the overall acceptability score of 8.1 ± 0.4 exceeding the threshold of 7.0/9 for commercial acceptability. The taste score of 8.5 ± 0.3 — the highest among all attributes — confirms that the film materials (corn starch, glycerine, beeswax) did not impart any off-flavour or undesirable taste to the seasoning. The relatively lower texture score (7.8 ± 0.6) is attributable to the slight waxy mouthfeel characteristic of beeswax-based edible films (Pérez-Vergara et al., 2020). These results confirm strong consumer acceptance of PODIBLE as a ready-to-use edible packaging system.

Table 6. Sensory evaluation scores for PODIBLE sachet (n=10, 9-point hedonic scale)

Attribute	Mean Score (9-point)	Interpretation	PODIBLE vs Control
Appearance	8.2 ± 0.4	Like very much	Superior
Texture	7.8 ± 0.6	Like moderately	Comparable
Taste	8.5 ± 0.3	Like very much	Superior
Overall acceptability	8.1 ± 0.4	Like very much	Superior

3.6 Microbiological Analysis

Microbiological analysis results are presented in Table 7. The PODIBLE sachet met all FSSAI microbiological safety standards. The total plate count of $<10^2$ CFU/g is within FSSAI permissible limits. The complete absence of yeast, mould, E. coli, and Salmonella confirms that the film preparation process maintains adequate hygiene and that the natural materials used do not support microbial growth under the tested storage conditions. The low water activity of the dried films effectively inhibits microbial proliferation.

Table 7. Microbiological analysis results for PODIBLE sachet

Test	Method Used	Result	FSSAI Limit
Total Plate Count (TPC)	Standard Plate Count, PCA	$<10^2$ CFU/g	$<10^2$ CFU/g
Yeast & Mould	Potato Dextrose Agar (PDA)	Absent	$<10^2$ CFU/g
E. coli	MacConkey / EMB Agar	Absent	Absent
Salmonella spp.	Selenite Broth / XLD Agar	Absent	Absent

3.7 Biodegradability Analysis

Biodegradability results are presented in Table 8. PODIBLE films demonstrated rapid and progressive biodegradation, achieving approximately 95% weight loss within 14 days under soil burial conditions. The degradation followed a characteristic sequence: moisture absorption and swelling (Day 0–3); surface cracking and structural weakening (Day 3–5); active microbial enzymatic degradation (Day 5–10); and near-complete disintegration by Day 14. The mechanism involves sequential hydrolysis of starch chains by amylase-producing soil microorganisms including Bacillus subtilis, Aspergillus niger, and Rhizopus species (Han, 2014). Pérez- Vergara et al. (2020) observed similar biodegradation profiles for cassava starch–beeswax films, with beeswax marginally slowing initial degradation rate while overall biodegradation remained highly favourable. The ~95% degradation within 14 days represents approximately 10,000 times faster degradation than conventional polyethylene sachets, which persist in the environment for 400–500 years.

Table 8. Biodegradability soil burial test results for PODIBLE film (Day 0 to Day 14)

Day	Visual Observation	Weight Loss (%)	Inference
0	Film intact; no change	~0%	Baseline
3	Slight swelling; edges softening	~8%	Moisture absorption initiated
5	Surface cracks; discolouration	~22%	Structural breakdown beginning
7	Partial fragmentation; ~40% degraded	~40%	Active microbial degradation
10	Major breakdown; ~75% degraded	~75%	Rapid starch hydrolysis
14	Nearly complete degradation; trace fragments	~95%	Near-complete biodegradation

3.8 Water Vapour Transmission Rate (WVTR)

WVTR results are presented in Table 9. The inner film exhibited a high WVTR of 1850 ± 50 g/m²/day, characteristic of hydrophilic corn starch–glycerine films. The outer film demonstrated a significantly lower WVTR of 720 ± 35 g/m²/day — a 61.1% reduction — directly attributed to beeswax incorporation. The statistically significant difference ($p < 0.05$) confirms the effectiveness of beeswax in impeding water vapour transmission, consistent with Gutiérrez (2015) and Pérez-Vergara et al. (2020). The contrasting WVTR values confirm the fundamental design rationale of the PODIBLE bilayer system: the high WVTR of the inner film facilitates rapid dissolution upon hot-water contact, while the low WVTR of the outer film provides storage moisture protection.

Table 9. Water Vapour Transmission Rate (WVTR) of PODIBLE inner and outer films (ASTM E96/E96M; 38°C, 90% RH)

Film Layer	WVTR ($g/m^2/day$)	Inference
Inner Film (Trial 9)	1850 ± 50	High WVTR — hydrophilic; suitable for dissolution but poor moisture barrier
Outer Film (Trial 4)	720 ± 35	61.1% lower than inner film — beeswax provides effective moisture barrier

3.9 Tensile Strength and Elongation at Break

Mechanical properties are presented in Table 10. The outer film exhibited significantly higher tensile strength (18.2 ± 1.1 MPa) compared to the inner film (12.5 ± 0.8 MPa; $p < 0.05$), attributed to the reinforcing effect of crystalline beeswax particles restricting polymer chain mobility. The inner film showed higher elongation at break (48 ± 3%) compared to the outer film (28 ± 2%), reflecting greater flexibility due to dominant glycerine plasticisation and absence of beeswax. These values are consistent with starch–glycerine film data reported by Aisyah (2017) and Sothornvit and Krochta (2005). The complementary mechanical profiles of the two layers produce a bilayer sachet with balanced structural and functional performance — the inner layer's flexibility facilitating folding and sealing, while the outer layer's strength maintains structural integrity during storage and handling.

Table 10. Tensile strength and elongation at break of PODIBLE inner and outer films (ASTM D882)

Film Layer	Tensile Strength (MPa)	Elongation at Break (%)	Inference
Inner Film (Trial 9)	12.5 ± 0.8	48 ± 3	Highly flexible; suitable for dissolution and handling
Outer Film (Trial 4)	18.2 ± 1.1	28 ± 2	Stronger; provides structural integrity as outer protective layer

3.10 Preliminary Shelf-Life Assessment

Shelf-life observations are presented in Table 11. The PODIBLE dual-layer sachet maintained acceptable food safety, structural integrity, and product quality for 75 days under ambient storage conditions (25–28°C, 55–65% RH). No microbial growth was detected throughout the 75-day period (TPC < 10^2 CFU/g; E. coli and Salmonella absent at all time points), confirming FSSAI compliance for the entire shelf-life duration. The seasoning powder remained free-flowing and aromatically acceptable up to Day 60, with acceptable usability maintained through Day 75. Progressive outer film softening at edges beyond Day 60 is consistent with gradual water vapour permeation through the beeswax–starch matrix over extended storage, defining the practical shelf-life endpoint at Day 75. This shelf-life performance is comparable to conventional plastic seasoning sachets, strongly supporting the commercial viability of PODIBLE.

Table 11. Preliminary shelf-life assessment of PODIBLE sachet under ambient storage (25–28°C, 55–65% RH)

Day	Sachet Condition	oisture (%)	Seasoning Condition	Inference
0	Intact; firm outer layer; well-sealed	~4.2	Free-flowing; strong aroma; no caking	Baseline — acceptable
7	No visible change; seal intact	~4.4	Free-flowing; aroma retained	Acceptable — no deterioration
14	Outer film slightly softened at edges	~4.6	Free-flowing; minor edge moisture noted	Acceptable — barrier functional
30	Minor surface flex; no seal failure	~5.0	Mostly free-flowing; aroma slightly reduced	Acceptable — quality maintained
45	Slight colour change at surface; no leakage	~5.5	Slight surface caking at edges; core free-flowing	Acceptable — within limits
60	Film slightly tacky; seal edges firm	~6.1	Moderate caking at periphery; aroma detectable	Borderline acceptable
75	Noticeable softening; seal intact; no leakage	~6.8	Caking at edges; central powder usable; aroma reduced	End of shelf life — 75 days

3.11 Cost Estimation

The raw material cost estimation is presented in Table 12. One batch of PODIBLE film preparation yields approximately 8 sachets at a total raw material cost of ₹7.00, giving a cost of ₹0.875 per sachet — effectively less than ₹1.00 per sachet. This is comparable to the retail cost of conventional single-use plastic seasoning sachets, confirming the economic viability of PODIBLE as a commercially competitive sustainable packaging alternative. At industrial scale, bulk material procurement and optimised production are expected to further reduce per-sachet cost.

Table 12. Raw material cost estimation per batch of PODIBLE sachets (8 sachets/batch; April 2026 market prices)

Material	Qty per Batch	Unit Cost (₹)	Cost per Batch (₹)
Corn starch	5 g	₹0.40/g	2.00
Glycerine	1 ml	₹1.00/ml	1.00
Beeswax	2 g	₹2.00/g	4.00
GMS	0.5 g	Trace amount	~0.00
Distilled water	100 ml	—	0.00
TOTAL	**—**	**—**	**₹7.00 (8 sachets)**

3.12 Summary of Key Results

Table 13 provides a consolidated summary of all key results obtained in this study, confirming that PODIBLE satisfies all functional, safety, environmental, and economic requirements for a viable sustainable food packaging system.

Table 13. Summary of key results — PODIBLE dual-layer edible sachet

Parameter	Result	Significance
Inner film thickness	0.28 ± 0.02 mm	Uniform thin film suitable for sachet construction
Outer film thickness	0.35 ± 0.03 mm	Adequate protective outer layer
Solubility (inner film)	~60 sec at 95°C	Rapid dissolution — direct consumption without sachet removal
Moisture gain (inner only)	12.5%	High — unsuitable alone for dry food packaging
Moisture gain (PODIBLE)	4.2%	66.4% improvement — effective protection against humidity
WVTR (inner)	1850 ± 50 g/m²/day	Hydrophilic; rapid dissolution characteristics
WVTR (outer)	720 ± 35 g/m²/day	61.1% reduction vs inner — beeswax barrier effective
Tensile strength (outer)	18.2 ± 1.1 MPa	Adequate for sachet construction and handling
Tensile strength (inner)	12.5 ± 0.8 MPa	Flexible; suitable for hot-water dissolution
Sensory — Overall	8.1 / 9	High consumer acceptability — 'Like very much'
TPC	<10² CFU/g	Microbiologically safe per FSSAI standards
Pathogens (E. coli, Salmonella)	Absent	Confirmed safe for food application
Biodegradation	~95% in 14 days	Rapid — 10,000× faster than conventional plastic sachets
Shelf life	75 days	Comparable to commercial plastic sachets
Cost per sachet	< ₹1.00	Economically competitive with conventional plastic packaging

4. Conclusion

The present study successfully developed and characterised PODIBLE — a biodegradable dual-layer edible bilayer film comprising a hydrophilic inner layer (corn starch + glycerine, Trial 9) and a hydrophobic outer layer (corn starch + beeswax + GMS, Trial 4) — as a sustainable and functional alternative to conventional single-use plastic seasoning sachets. The PODIBLE dual-layer sachet achieved rapid inner-layer dissolution in hot water within 60 seconds with no solid residue, a 66.4% improvement in moisture barrier performance (moisture gain reduced from 12.5% to 4.2%), a significant reduction in WVTR (1850 to 720 g/m²/day; 61.1%), and adequate mechanical strength (18.2 ± 1.1 MPa tensile strength for the outer film) for practical sachet construction and handling. Sensory evaluation confirmed high consumer acceptability (overall score 8.1/9), and microbiological analysis established FSSAI compliance with complete absence of pathogenic organisms.

Biodegradability testing demonstrated near-complete degradation (~95% weight loss) within 14 days under soil burial conditions — approximately 10,000 times faster than conventional plastic sachets, which persist for 400–500 years. A 75-day preliminary shelf-life was confirmed under ambient storage conditions. The raw material cost of <₹1.00 per sachet positions PODIBLE as economically competitive with conventional plastic packaging. The novelty of PODIBLE has been formally recognised through an Ordinary Patent Application filed with the Patent Office of India (Application No. 202641030135, dated 13 March 2026, Chennai Branch). The findings of this study establish a strong scientific and technical foundation for the further development, scale-up, and commercialisation of the PODIBLE technology, with direct relevance to India's regulatory imperative under the Plastic Waste Management Rules (2016, amended 2021) and the global transition towards sustainable food packaging.

Acknowledgements
The authors sincerely acknowledge the support of Dr. P. Balamurugan (Head of Department), the teaching staff of the Department of Food Technology, JCT College of Engineering and Technology, Coimbatore, and their families for their constant encouragement throughout this work.

Conflicts of Interest: The authors declare no conflicts of interest.

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