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Drying effects on physicochemical and techno-functional properties of *Terminalia arjuna* leaf mucilage in set yoghurt

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Abstract: Stabilisers are widely used in yoghurt production to improve texture, consistency, and gel stability while minimising syneresis. Although gelatine is commonly applied for this purpose, ethical and sustainability concerns have increased interest in plant-based alternatives. This study evaluated *Terminalia arjuna* leaf mucilage powders as a natural stabiliser in set yoghurt. Mucilage was dried by freeze drying, microwave drying, and oven drying, incorporated at 0.6–1.0% (*w/w*), and compared with gelatine-stabilised yoghurt for physicochemical, textural, and sensory properties. The drying method and concentration significantly affected yoghurt quality. Yoghurt containing 1.0% freeze-dried mucilage powder showed the highest water-holding capacity (58.40 ± 0.10%) and lowest syneresis (22.10 ± 0.10%), with sensory and proximate characteristics comparable to the gelatine control. These results demonstrate that freeze-dried *T. arjuna* leaf mucilage, at an optimised concentration, is a promising plant-based alternative to gelatine in set yoghurt.

Keywords: fermented dairy product; gelatine substitute; plant hydrocolloid; syneresis; water holding capacity

Yoghurt is one of the most widely consumed fermented dairy products globally, valued for its nutritional quality, health benefits, and versatility in human diets. Desirable textural attributes such as viscosity, stability, and gel firmness are achieved through increased milk solids and protein content; however, in some industrial yoghurt formulations, stabilisers, starches, and polysaccharide-based hydrocolloids are additionally incorporated to further enhance texture and reduce syneresis (Li et al. 2025). Among these, gelatine has been widely used for its effective gelling properties, which enhance mouthfeel, structural integrity, and sensory acceptability in yoghurt products.

However, ethical, religious, and sustainability concerns associated with animal-derived ingredients have limited the acceptability of gelatine in food products. As a result, there is growing interest in natural, plant-based alternatives that provide comparable functional performance (Samanmali and Kananke 2025). In this context, plant-derived mucilage and gums have re-

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ceived considerable attention for their ability to enhance viscosity, texture, and stability in food systems, including fermented dairy products (Saha and Bhattacharya 2010).

Mucilage extracted from *Terminalia arjuna*, a food plant native to the Indian subcontinent, represents a potential plant-based stabiliser. *T. arjuna* has been traditionally used in Ayurvedic medicine and is reported to have antioxidant, anti-inflammatory, and cardioprotective properties (Ramesh and Palaniappan 2023). *T. arjuna* leaves contain phytochemicals such as flavonoids and glycosides, including luteolin and 14,16-dianhydrogitoxigenin 3-β-ᴅ-xylopyranosyl-(1→2)-O-β-ᴅ-galactopyranoside (Amalraj and Gopi 2017). Although detailed compositional data for *T. arjuna* leaf mucilage are limited, it is primarily composed of polysaccharides with minor constituents such as hydrolysable tannins and triterpenoids (Wijerathne et al. 2018). While its use in fermented milk products remained largely unexplored, it has been applied as an edible coating, demonstrating film-forming and water-binding properties (Wijerathne et al. 2018). Hydrolysable tannins may further contribute to functional behaviour through interactions with proteins in food systems (Amalraj and Gopi 2017). Previous studies have reported that plant-derived mucilage can improve yoghurt viscosity, firmness, water-holding capacity, and sensory quality while reducing syneresis (Cakmak et al. 2023). However, the direct incorporation of fresh mucilage into yoghurt has been associated with practical limitations, including increased syneresis and reduced storage stability. Converting mucilage into a dehydrated powder using appropriate drying techniques offers an effective strategy to address these challenges.

Powdered mucilage provides advantages such as improved shelf life, ease of handling, uniform dispersion, and more consistent functional performance during yoghurt manufacture. Powder formulation also facilitates optimisation of concentration levels to achieve targeted rheological and sensory properties, while reducing raw material waste and supporting cost-effective, sustainable production (Yekta and Ansari 2019). As drying strongly influences molecular integrity, solubility, and functionality of plant mucilage, systematic evaluation of drying techniques is essential; however, limited studies have compared different drying methods in relation to their impact on mucilage performance in food systems. In this context, freeze drying, microwave-assisted drying, and oven drying were selected to represent low-temperature preservation, rapid thermal processing, and conventional hot-air drying, respectively. Accordingly, the present study aimed to investigate how different drying methods influence the physicochemical and techno-functional properties of *Terminalia arjuna* leaf mucilage, and to assess the suitability of the selected formulation as a gelatine substitute in set yoghurt systems.

MATERIAL AND METHODS

Raw material collection. Fresh *T. arjuna* leaves (Figure 1) were collected from the Pambahinna area, Sri Lanka (GPS coordinates: 6.7146°N, 80.7872°E). Fresh cow's milk (≈ 3.5% fat) was obtained from the dairy farm of Sabaragamuwa University of Sri Lanka, Pambahinna. A commercial ABT-5 culture (Chr. Hansen, Denmark), containing *Streptococcus thermophilus, Lactobacillus acidophilus* and *Bifidobacterium* spp., was used as a probiotic starter culture, as an alternative to traditional yoghurt culture. Food-grade gelatine was obtained from Sigma-Aldrich, USA. All chemical reagents used were of analytical grade.

Extraction of *T. arjuna* leaf mucilage. The collected leaves were thoroughly washed to remove contaminants. The leaves were cut into 2–3 cm segments and soaked in distilled water (1 : 2 *w/v*) at room temperature (28 ± 2 °C) with continuous stirring for 30 min. The hydrated mass was manually pressed using a sterile muslin cloth to extract mucilage, followed by filtration through double-layer cheesecloth to remove insoluble plant residues. The mucilage was stored at 4 °C until further processing.

Figure 1. *Terminalia arjuna* leaves

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Drying of mucilage. The drying methods were selected to represent contrasting dehydration mechanisms relevant to food processing. A single homogeneous batch (1.5 L) of extracted mucilage was divided into three equal portions (500 mL each) and subjected to freeze drying, microwave drying, and oven drying. Oven drying was included as a conventional, low-cost benchmark, while microwave and freeze drying represent rapid thermal and low-temperature dehydration approaches, respectively. Freeze drying was performed using a freeze dryer (Labogene CoolSafe Pro 95-15, Denmark). The samples were pre-frozen at –80 °C for 24 h and subsequently dried at a condenser temperature of –50 °C and a pressure of 0.04 mbar for 48 h until complete sublimation was obtained. Microwave drying was carried out in a microwave oven (Panasonic NN-CT645B, Japan) at 600 W for 10 min, with intermittent mixing at every 2-minute intervals, maintaining a mucilage layer thickness of 3–4 mm, until constant weight was reached. Oven drying was performed in a hot-air oven (Memmert UF30, Germany) at 60 °C, for about 24 h, with a 3–4 mm layer thickness and drying was continued until constant weight. All dried samples were ground, sieved through a 500 µm mesh, and stored in airtight containers at room temperature until further analysis.

Characterisation of mucilage powders. Mucilage powder yield was calculated as the ratio of dried mucilage powder weight to fresh leaf weight. Moisture content was determined following the AOAC method 925.10 (2019). Solubility was assessed by dispersing a known quantity of powder in water and measuring the undissolved residue after filtration. pH was measured using a calibrated digital pH meter (Hanna Instruments HI2211, Romania), and titratable acidity was evaluated by titrating with 0.1 M NaOH (Antigo et al. 2020). The apparent viscosity of 1% (*w/v*) mucilage solutions was measured at 25 °C using a rheometer (Anton Paar RheolabQC, Austria) equipped with a concentric cylinder geometry (CC27) at a constant shear rate of 100 s^{-1}. Reducing sugar content of mucilage powders was determined using the 3,5-dinitrosalicylic acid (DNS) method. Functional groups and structural changes induced by drying were analysed using Fourier Transform Infrared (FTIR) spectroscopy (Bruker Tensor 27 spectrometer, Germany).

Yoghurt preparation. Yoghurt samples were prepared according to the standard set-yoghurt manufacturing procedure with slight modifications (Samanmali and Kananke 2025). Fresh cow's milk was filtered and added with mucilage powders obtained by freeze drying, microwave drying, and oven drying at concentrations of 0.6, 0.8, and 1.0% (*w/w*), followed by thorough mixing to ensure uniform dispersion. The mixtures were then heated to 95 °C for 10 min with gentle stirring to ensure whey protein denaturation and microbial safety, then cooled to 42 °C. A yoghurt sample containing gelatine (0.6%, *w/w*) was prepared as the control formulation under the same conditions. The milk mixtures were inoculated with ABT-5 starter culture at ~3% (*v/v*), gently mixed, and incubated at 37–42 °C until pH reached approximately 4.6 (4–6 h). The prepared yoghurt samples were subsequently stored at 4 °C prior to further analyses.

Fermentation kinetics and acidification behaviour of yoghurt formulations. Fermentation kinetics of yoghurt formulations containing *T. arjuna* leaf mucilage were evaluated by monitoring pH decline and titratable acidity during incubation. Yoghurt was prepared as described earlier and incubated at 37–42 °C under static conditions. Initial pH was recorded immediately after inoculation and pH was monitored at 30-min intervals until pH 4.6 was reached, defined as the fermentation end point, and the corresponding time (TpH4.6) was recorded (Samanmali and Kananke 2025). Fermentation was continued for a total of 6 h, after which final pH was measured. Fermentation parameters (initial pH, TpH4.6, final pH, and titratable acidity) were used to assess the effects of mucilage drying method and concentration relative to gelatine-stabilised yoghurt.

Colour and texture analysis of yoghurt. Colour values (L^*, a^*, b^*) were measured using a colorimeter (Konica Minolta CR-400, Japan). Measurements were conducted under D65 illumination with a 10° standard observer. Yoghurt samples were placed in a uniform layer (~10 mm thickness) in a flat container, and readings were taken against a white background. L^*, a^*, b^* values were recorded at three different locations for each sample, and measurements were performed in triplicate. Textural properties were evaluated using a texture profile analyser (Brookfield CT3, AMETEK Inc., USA), using a two-cycle compression test with repeated probe insertion. A cylindrical probe (38 mm diameter) was used at 30% strain and a speed of 1 mm·s^{-1}. Yoghurt samples were analysed in cylindrical yoghurt containers (45 mm diameter, 55 mm height) for texture parameters including hardness, adhesiveness, cohesiveness, and gumminess (Hussain et al. 2022).

Water-holding capacity and syneresis. Water-holding capacity was determined by centrifuging 5 g of yoghurt at 5000 × g for 30 min. The released whey was decanted, and the remaining gel fraction

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was weighed to calculate the proportion of retained mass, which was used as an indicator of water retention capacity. Syneresis was evaluated by measuring whey separation after 6 h of drainage at room temperature using a funnel and filter paper method (Samanmali and Kananke 2025).

Sensory evaluation. Sensory evaluation was conducted as a preliminary comparative assessment, focusing on the best-performing mucilage formulation, selected based on prior physicochemical and functional assessment, and the gelatine control (0.6%) to evaluate its suitability as a plant-based alternative. The test was performed in individual sensory booths under controlled lighting conditions, using 40 untrained panellists (university undergraduates, aged 20–30 years) who were regular yoghurt consumers. Samples were prepared under identical conditions and served in coded 50 mL cups (approx. 30 g) at 10 ± 2 °C in randomised order. Panellists were provided with water for palate cleansing between samples. Sensory attributes (appearance, colour, taste, aroma, texture on spoon, mouthfeel, and overall acceptability) were assessed using a five-point hedonic scale (1 = dislike very much, 5 = like very much). Sensory data were analysed using the Wilcoxon signed-rank test at a significance level of $P < 0.05$.

Proximate analysis. The proximate composition of the selected yoghurt formulation was determined following standard AOAC (2019) procedures: moisture (AOAC 925.10), ash (AOAC 923.03), crude protein (AOAC 991.20), crude fat (AOAC 989.05), and crude fibre (AOAC 962.09) were analysed. Carbohydrate content was calculated by difference.

Statistical analysis. All experimental procedures (mucilage extraction, drying, yoghurt preparation, and analytical measurements) were conducted in triplicate. The data are reported as mean ± SD. Differences among treatment means were determined by ANOVA, with subsequent Tukey's mean comparison test. Statistical significance was determined at $P < 0.05$.

RESULTS AND DISCUSSION

Yield of mucilage powders obtained from different drying mechanisms

The yield of *T. arjuna* mucilage powder varied with the drying method, following the order FDMP (freeze-dried mucilage powder) > MDMP (microwave-dried mucilage powder) > ODMP (oven-dried mucilage powder) (Table 1).

The higher yield observed in freeze drying is attributed to minimal thermal degradation and reduced material loss under vacuum conditions (Antigo et al. 2020). In contrast, the lower yield in oven drying may be due to prolonged heat exposure, structural degradation of polysaccharides and adhesion losses to drying surfaces. Microwave drying resulted in intermediate yield, likely due to rapid heating and localised thermal effects and partial loss of soluble components (Felkai-Haddache et al. 2016).

Physicochemical properties of mucilage powders

The physicochemical properties of *T. arjuna* mucilage powders were significantly affected by the drying method (Table 2). FDMP showed the lowest moisture content (2.40 ± 0.14%), followed by MDMP (6.10 ± 0.13%) and ODMP (8.70 ± 0.07%). The low moisture content of FDMP is attributed to sublimation under vacuum, whereas higher moisture retention in ODMP may result from case hardening and restricted moisture diffusion during hot-air drying of polysaccharide-rich materials (Ahmed et al. 2018; Antigo et al. 2020).

Solubility, apparent viscosity, titratable acidity, and reducing sugar content of *T. arjuna* mucilage were significantly influenced by drying method, while pH change was not significant (6.10–6.61; $P > 0.05$). Solubility and viscosity decreased in the order freeze-dried > microwave-dried > oven-dried, with freeze-dried mucilage showing the highest solubility (94.0 ± 1.41%) and viscosity (2.40 ± 0.14 Pa·s), attributed to porous, amorphous structures and better retention of high molecular-weight polysaccharides (Antigo et al. 2020). Lower solubility (80.6 ± 0.42%) and viscosity in oven-dried samples were associated with possible thermal aggregation and depolymerisation of polysaccharides, while microwave drying showed intermediate effects due to rapid heating (Felkai-Haddache et al. 2016). Titratable acidity increased from freeze-dried to oven-dried mucilage, likely due to thermal modification of polysaccharides and increased availability of acidic groups (Ahmed et al. 2018). Reducing

Table 1. Yield of mucilage powders obtained by different drying techniques

Sample	Yield (%)
Oven-dried mucilage powder (ODMP)	0.85
Microwave-dried mucilage powder (MDMP)	1.29
Freeze-dried mucilage powder (FDMP)	1.77

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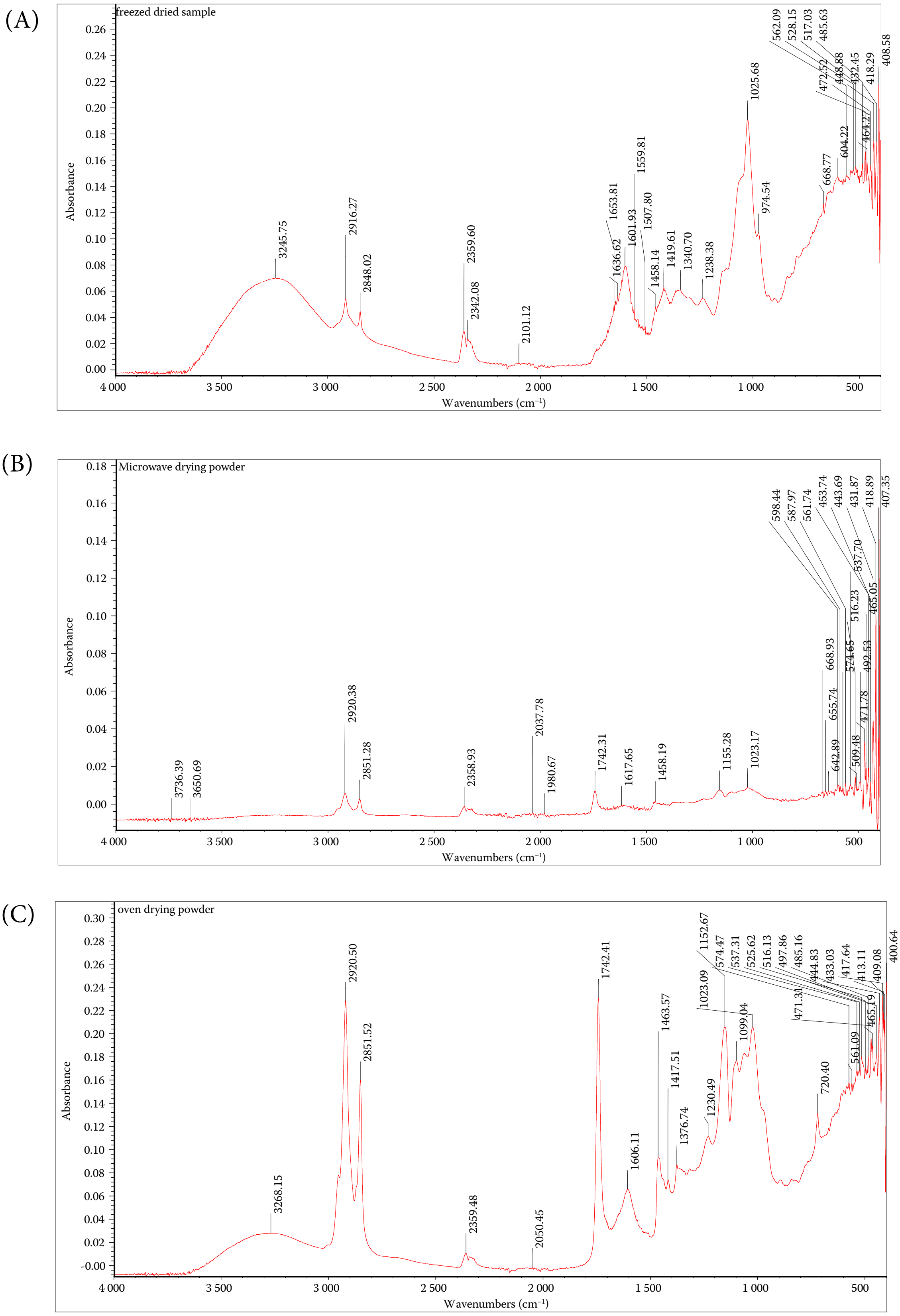

Figure 2. FTIR spectra for (A) FDMP, (B) MDMP and (C) ODMP

FTIR – Fourier transform infrared spectroscopy; FDMP – freeze-dried mucilage powder; MDMP – microwave-dried mucilage powder; ODMP – oven-dried mucilage powder

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Table 2. Physicochemical properties of mucilage powders

	FDMP	MDMP	ODMP
Moisture content (%)	2.40 ± 0.14^c	6.10 ± 0.13^b	8.70 ± 0.07^a
Solubility (%)	94.0 ± 1.41^a	86.0 ± 1.62^{ab}	80.6 ± 0.42^b
pH	6.61 ± 0.07^a	6.40 ± 0.14^a	6.10 ± 0.21^a
Titratable acidity (mg NaOH·g^{-1})	0.46 ± 0.01^a	0.52 ± 0.00^b	0.61 ± 0.01^c
Apparent viscosity (Pa.s) (at 25 °C, 1% solution)	2.40 ± 0.14^a	1.85 ± 0.07^b	1.15 ± 0.07^c
Reducing sugar content [g glucose eq.·(100 g)$^{-1}$ dry mucilage]	5.56 ± 0.11^a	3.80 ± 0.10^b	2.25 ± 0.20^c

$^{a-c}$different letters in the same row indicate significant differences ($P < 0.05$); data are presented as mean ± SD ($n = 3$); FDMP – freeze-dried mucilage powder; MDMP – microwave-dried mucilage powder; ODMP – oven-dried mucilage powder

sugar content was highest in freeze-dried mucilage [5.56 ± 0.11 g glucose eq.·(100 g)$^{-1}$], followed by microwave- and oven-dried samples, consistent with sugar degradation and non-enzymatic browning under heat exposure.

FTIR characterisation of mucilage powders

The FTIR spectra of *T. arjuna* mucilage powders obtained by freeze drying (Figure 2A), microwave drying (Figure 2B), and oven drying (Figure 2C) showed clear differences in peak intensity and band resolution, indicating the influence of drying method on functional group distribution in mucilage polysaccharides.

All samples showed a broad O-H stretching band at 3 200–3 400 cm^{-1} typical of polysaccharides, with higher intensity in FDMP, indicating better retention of hydrophilic groups and hydrogen bonding. Attenuation of this band and of C-H stretching bands (2 920–2 850 cm^{-1}) in MDMP and ODMP suggests thermal disruption of hydrogen-bonding networks and conformational rearrangements (Saha and Bhattacharya 2010; Santos et al. 2023). Bands at 1 700–1 600 cm^{-1} and 1 410–1 380 cm^{-1}, assigned to carboxyl and carboxylate groups, were more intense in FDMP, while reduced intensity and minor shifts in thermally dried samples indicate heat-induced modification of acidic functional groups relevant to hydration and gelling behaviour. The fingerprint region (1 200–900 cm^{-1}), associated with glycosidic linkages, showed stronger and better-resolved bands in FDMP (≈ 1 020–1 040 cm^{-1}), whereas thermal drying caused reduced intensity and resolution, consistent with partial depolymerisation and increased structural disorder (Santos et al. 2023). Overall, freeze drying preserved functional groups critical for hydration, viscosity, and gel formation more effectively than thermal methods.

Fermentation kinetics and acidification behaviour of yoghurt formulations

Fermentation kinetics (Table 3) showed that gelling agent type and concentration significantly af-

Table 3. Fermentation kinetics of yoghurt formulations during incubation at 37–42 °C

Sample	Initial pH (0 h)	Time to pH 4.6 (h)	Final pH (6 h)	Final TA (% lactic acid)
FDMP 0.6%	6.62 ± 0.02^b	4.6 ± 0.1^c	4.30 ± 0.01^c	0.86 ± 0.01^e
FDMP 0.8%	6.61 ± 0.02^{bc}	4.4 ± 0.1^d	4.28 ± 0.01^d	0.89 ± 0.01^d
FDMP 1.0%	6.60 ± 0.02^c	4.2 ± 0.1^e	4.25 ± 0.02^e	0.93 ± 0.01^b
MDMP 0.6%	6.63 ± 0.03^b	4.8 ± 0.1^b	4.33 ± 0.02^b	0.88 ± 0.01^{de}
MDMP 0.8%	6.62 ± 0.02^b	4.6 ± 0.1^c	4.31 ± 0.01^c	0.91 ± 0.01^c
MDMP 1.0%	6.61 ± 0.02^{bc}	4.4 ± 0.1^d	4.26 ± 0.01^{de}	0.94 ± 0.01^b
ODMP 0.6%	6.64 ± 0.03^{ab}	5.0 ± 0.1^a	4.35 ± 0.01^b	0.87 ± 0.01^e
ODMP 0.8%	6.63 ± 0.02^{ab}	4.8 ± 0.1^b	4.32 ± 0.01^c	0.90 ± 0.01^{cd}
ODMP 1.0%	6.62 ± 0.02^b	4.5 ± 0.1^{cd}	4.29 ± 0.01^d	0.95 ± 0.01^a
Gelatine 0.6%	6.65 ± 0.03^a	5.2 ± 0.1^a	4.46 ± 0.01^a	0.88 ± 0.01^{de}

$^{a-e}$different letters within the same column indicate significant differences ($P < 0.05$); data are presented as mean ± SD ($n = 3$); FDMP – freeze-dried mucilage powder; MDMP – microwave-dried mucilage powder; ODMP – oven-dried mucilage powder; TA – titratable acidity

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Table 4. L^*, a^*, b^* values for yoghurt samples

Sample	L^* value	a^* value	b^* value
FDMP 0.6%	83.70 ± 1.76[c]	−2.08 ± 0.13[cd]	12.50 ± 0.75[f]
FDMP 0.8%	79.68 ± 0.51[de]	−1.73 ± 0.10[c]	15.20 ± 0.17[d]
FDMP 1.0%	90.51 ± 0.21[a]	−2.07 ± 0.03[cd]	12.99 ± 0.15[ef]
MDMP 0.6%	73.74 ± 0.24[g]	−0.26 ± 0.10[b]	13.68 ± 0.16[e]
MDMP 0.8%	77.92 ± 0.32[efg]	−0.29 ± 0.07[ab]	13.86 ± 0.11[ef]
MDMP 1.0%	79.22 ± 0.78[de]	−0.08 ± 0.29[ab]	12.74 ± 0.32[ef]
ODMP 0.6%	65.46 ± 1.32[h]	0.15 ± 0.19[ab]	16.42 ± 0.43[c]
ODMP 0.8%	74.81 ± 0.24[fg]	−0.20 ± 0.04[ab]	18.22 ± 0.08[b]
ODMP 1.0%	60.14 ± 0.89[i]	0.58 ± 0.58[a]	21.20 ± 0.12[a]
Gelatine 0.6%	81.14 ± 0.38[cd]	−2.71 ± 0.12[d]	12.62 ± 0.35[ef]

[a–g]different letters within the same column indicate significant differences ($P < 0.05$); data are presented as mean ± SD ($n = 3$); FDMP – freeze-dried mucilage powder; MDMP – microwave-dried mucilage powder; ODMP – oven-dried mucilage powder

fected yoghurt acidification ($P < 0.05$). Initial pH values of mucilage-containing formulations were not significantly different (6.60–6.64), indicating that differences in acidification were probably due to stabiliser–matrix interactions rather than starter activity (Lucey 2002). FDMPs exhibited the shortest TpH4.6 (4.6–4.2 h from 0.6–1.0%), with lower final pH and higher titratable acidity, consistent with enhanced solubility, hydration, and mass transfer of freeze-dried polysaccharides (Antigo et al. 2020). MDMPs showed intermediate fermentation times (4.8–4.4 h), while ODMPs resulted in slower acidification, particularly at lower concentrations. These differences are attributed to structural modifications of mucilage induced by drying, which may influence viscosity, water mobility, and mass transfer within the yoghurt matrix, thereby affecting microbial activity and acidification kinetics (Ahmed et al. 2018; Antigo et al. 2020; Santos et al. 2023). The gelatine control showed the slowest acidification (TpH4.6 = 5.2 h) and higher final pH, reflecting its non-fermentable and buffering nature (Lucey 2002; Nguyen et al. 2017). The higher final titratable acidity observed in mucilage-stabilised yoghurts can be partly attributed to the intrinsic acidity of the added mucilage, which contributes to overall titratable acidity, in addition to fermentation-derived lactic acid (Wang et al. 2025).

Evaluation of physicochemical properties of yoghurt

Colour measurements. Colour parameters (L^*, a^*, b^*) of yoghurt were significantly affected by drying method and mucilage concentration (Table 4).

FDMP (1.0%) demonstrated higher L^* values, reflecting higher lightness due to low thermal impact and enhanced light scattering (Antigo et al. 2020), whereas MDMP and ODMP exhibited reduced L^*, reflecting heat-induced darkening probably associated with Maillard reactions and pigment concentration (Ahmed et al. 2018). Most samples had negative a^* values typical of plain yoghurt; however, ODMP at higher levels shifted toward positive a^*, indicating reddish hues likely due to thermal degradation of phenolics and pigment formation (Ahmed et al. 2018; Wang et al. 2025). Gelatine and FDMP yoghurts maintained more negative a^* values, indicating better colour neutrality. Increased b^* values in ODMP samples reflected enhanced yellowness, possibly due to thermal browning, carotenoid concentration, and protein–polyphenol interactions, while FDMP caused minimal colour changes.

Textural properties. Textural properties of yoghurt were significantly influenced by stabiliser type, drying method, and concentration ($P < 0.05$; Table 5). Hardness values (194.60–590.30 g) were comparable to those reported for yoghurts containing gelatine and plant-based stabilisers (Ge et al. 2022). The highest hardness was observed in gelatine-stabilised yoghurt and the FDMP 1.0% formulation, indicating the formation of dense and well-connected gel networks. In contrast, MDMP and ODMP samples, at higher concentrations, exhibited reduced hardness, with the lowest value observed in ODMP 1.0%, suggesting a weakened gel structure likely due to heat-induced structural modifications and reduced polymer functionality (Hussain et al. 2022).

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Table 5. Textural properties of yoghurt samples

Sample	Hardness (g)	Adhesiveness (g.s)	Cohesiveness	Gumminess (g)
FDMP 0.6%	447.67 ± 7.51[d]	93.93 ± 1.32[b]	0.56 ± 0.01[b]	250.20 ± 1.81[c]
FDMP 0.8%	501.67 ± 7.64[c]	81.23 ± 0.75[c]	0.58 ± 0.01[a]	291.80 ± 2.03[b]
FDMP 1.0%	584.23 ± 5.75[a]	67.53 ± 0.70[d]	0.59 ± 0.01[a]	344.70 ± 1.60[a]
MDMP 0.6%	331.47 ± 10.32[f]	69.40 ± 1.40[d]	0.51 ± 0.01[c]	170.63 ± 5.12[e]
MDMP 0.8%	361.53 ± 6.50[f]	49.23 ± 1.25[e]	0.48 ± 0.01[d]	170.40 ± 2.51[e]
MDMP 1.0%	237.60 ± 2.51[g]	45.40 ± 0.60[f]	0.58 ± 0.01[a]	137.10 ± 2.01[f]
ODMP 0.6%	570.07 ± 5.00[b]	52.00 ± 2.00[e]	0.51 ± 0.01[c]	290.97 ± 5.00[b]
ODMP 0.8%	351.53 ± 6.50[e]	44.00 ± 2.00[f]	0.52 ± 0.02[c]	253.43 ± 4.50[c]
ODMP 1.0%	194.60 ± 2.51[h]	10.40 ± 0.40[g]	0.48 ± 0.01[d]	93.03 ± 2.00 [g]
Gelatine 0.6%	590.30 ± 0.99[a]	125.40 ± 0.60[a]	0.57 ± 0.00[a]	336.43 ± 1.40[a]

[a–g]different letters within the same column indicate significant differences ($P < 0.05$); data are presented as mean ± SD (n = 3); FDMP – freeze-dried mucilage powder; MDMP – microwave-dried mucilage powder; ODMP – oven-dried mucilage powder

Adhesiveness was highest in gelatine yoghurt, while microwave and oven dried mucilage formulations, showed lower values, indicating reduced surface stickiness, consistent with previous reports on gelatine replacement by plant polysaccharides (Nguyen et al. 2017). Cohesiveness ranged from 0.48 to 0.59, with higher values in FDMP 1% and gelatine 0.6%, indicating more stable and integrated gel matrices. Gumminess followed a similar trend to hardness and cohesiveness, with ODMP 1.0% exhibiting the lowest mechanical stability (Ge et al. 2022). Overall, increasing FDMP concentration improved

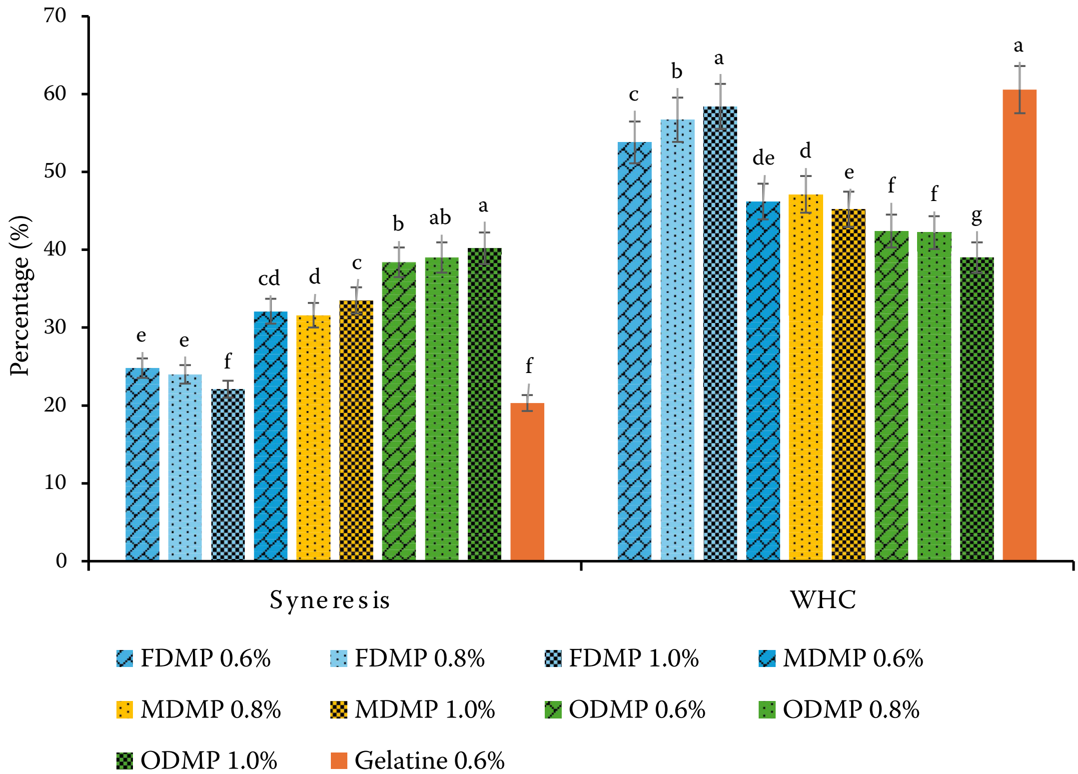

Figure 3. Syneresis (%) and water holding capacity (WHC, %) of yoghurt formulations

[a–g]different letters within each parameter indicate significant differences ($P < 0.05$); values are presented as mean ± SD (n = 3); error bars represent standard deviation; FDMP – freeze-dried mucilage powder; MDMP – microwave-dried mucilage powder; ODMP – oven-dried mucilage powder

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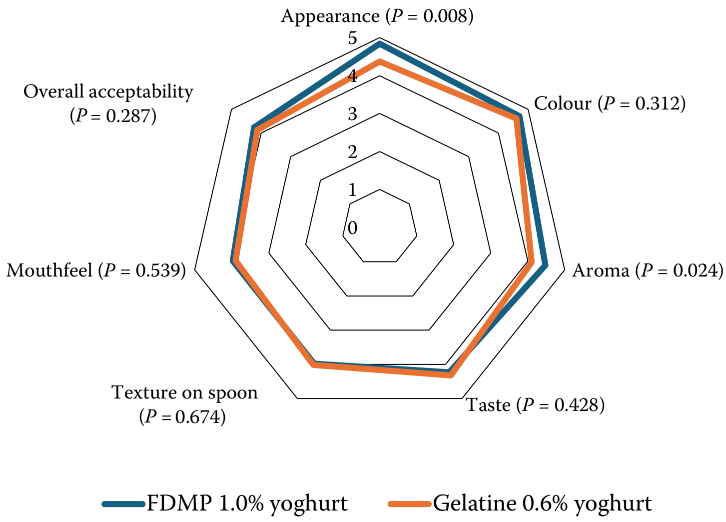

Figure 4. Radar plot showing sensory evaluation scores of yoghurt samples prepared with freeze-dried mucilage powder (FDMP, 1%) and gelatine (0.6%)

Sensory attributes were evaluated using a five-point hedonic scale ranging from 1 to 5 (1 = dislike very much; 5 = like very much)

textural properties, whereas MDMP and ODMP showed a declining trend.

Syneresis and water holding capacity (WHC) of yoghurt formulations. Syneresis and WHC, key indicators of yoghurt gel stability, differed significantly among formulations ($P < 0.05$; Figure 3).

Sample FDMP 1.0% showed the lowest syneresis (22.10%), statistically comparable to the gelatine control (20.32%), along with high WHC (58.40%), indicating efficient water immobilisation and a stable gel network. This behaviour may be associated with the retention of hydrophilic functional groups and hydration capacity in freeze-dried hydrocolloids, which enhance protein–polysaccharide interactions and reduce whey separation (Kaur and Riar 2020; Ge et al. 2022). Microwave-dried samples exhibited intermediate syneresis (31.6–33.5%) and WHC (45.2–47.1%), suggesting a moderate gel stability, possibly due to partial structural modification of polysaccharides during microwave processing that improves dispersibility but limits network strength (Li et al. 2025). In contrast, oven-dried samples showed the highest syneresis (38.4–40.2%) and lowest WHC (39.0–42.4%), indicating reduced serum entrapment, which may result from heat-induced depolymerisation or aggregation that weakens protein–polysaccharide interactions (Ahmed et al. 2018; Macit et al. 2019). According to results, freeze-dried mucilage exhibited a concentration-dependent improvement in gel stability, whereas thermally dried mucilage showed adverse effects at higher concentrations, indicating structural degradation and reduced compatibility with the protein matrix.

Sensory analysis

Sensory evaluation was conducted using the best-performing formulation containing freeze-dried mucilage (FDMP, 1.0%) and the gelatine control (0.6%). FDMP (1.0%) was selected based on superior physicochemical and functional properties, including higher WHC, lower syneresis, improved texture, and favourable fermentation behaviour. This comparison was performed to assess the suitability of FDMP as a plant-based alternative to gelatine.

Sensory evaluation indicated that FDMP (1.0%) yoghurt exhibited comparable scores to the gelatine control (0.6%) for most sensory attributes, including colour, taste, texture on spoon, mouthfeel, and overall acceptability ($P > 0.05$) (Figure 4). However, significant differences were observed for appearance and aroma ($P < 0.05$), with FDMP 1.0% showing higher preference scores. The similarity in key sensory attributes suggests that freeze-dried *T. arjuna* mucilage can effectively mimic the functional role of gelatine without adversely affecting consumer perception.

Proximate analysis

Proximate analysis of yoghurt prepared with FDMP 1.0% and gelatine showed values within the typical range reported for set yoghurt, with some differences attributable to the stabiliser used (Table 6).

Moisture content did not differ significantly between formulations ($P > 0.05$) and remained within the expected range for set yoghurt (80–85%). The slightly lower moisture content of FDMP 1.0% is consistent with its higher water-holding capacity and reduced syneresis, as reported for mucilage and fibre-enriched yoghurts (Kaur and Riar 2020). Crude protein and

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Table 6. Proximate analysis of yoghurt

Proximate constituent (%)	FDMP 1.0% yoghurt	Gelatine yoghurt
Moisture	81.25 ± 0.41[a]	82.85 ± 0.32[a]
Crude protein	3.40 ± 0.16[a]	3.60± 0.12[a]
Crude fat	3.12 ± 0.19[a]	3.05 ± 0.15[a]
Ash	0.72 ± 0.12[a]	0.60 ± 0.10[a]
Crude fibre	0.56 ± 0.03[a]	0.02 ± 0.02[b]
Carbohydrate	11.95 ± 0.02[a]	9.88± 0.02[b]

[a–b]different letters within the same row indicate significant differences ($P < 0.05$); data are presented as mean ± SD ($n = 3$); FDMP – freeze-dried mucilage powder

fat contents were not significantly affected by mucilage incorporation and were comparable to values reported for whole-milk and gelatine-stabilised yoghurts (Lucey 2002), indicating that mucilage functioned primarily as a stabiliser rather than a macronutrient replacer. Ash content showed no significant difference between samples. FDMP 1.0% exhibited significantly higher crude fibre and carbohydrate contents than the gelatine yoghurt ($P < 0.05$), reflecting the presence of non-digestible polysaccharides in plant mucilage (Kaur and Riar 2020).

CONCLUSION

This study demonstrates that *T. arjuna* leaf mucilage, particularly in freeze-dried form, is a promising plant-based alternative to gelatine in set yoghurt, with functional performance strongly influenced by the drying method. The results support its potential use in clean-label dairy products aligned with ethical and sustainability goals. As this work focused on technological functionality, food-relevant safety evaluation is required before broader application. Future research should focus on detailed compositional analysis of mucilage, microbial behaviour during storage, process scale-up, shelf life evaluation, and detailed microstructural and rheological characterisation, as well as applications in other dairy and plant-based systems.

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