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ORIGINAL PAPER

Aqueous extraction optimisation of okra (*Abelmoschus esculentus*) mucilage for food processing applications: rheological, FTIR, and TGA characterisation

Nelly Virginia Nkosi[1] · **Frederick Tawi Tabit**[1]

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Abstract

Hydrocolloids, such as plant mucilage, are increasingly utilised in food and non-food applications due to their multifunctional properties, including thickening, emulsifying, and foaming. However, limited availability and processing challenges have prompted exploration of alternative sources and optimised extraction techniques. This study aimed to optimise the extraction conditions of crude okra *(Abelmoschus esculentus*) mucilage using Response Surface Methodology (RSM) and to characterise its rheological properties and structural composition via Fourier-transform infrared (FTIR) spectroscopy. A Central Composite Design was used to evaluate the extraction temperature (X_1), okra mass (X_2), and water volume (X_3) as independent variables, with mucilage yield (Y) as the response variable. Rheological measurements were performed using a Brookfield RST-SST Rheometer and modelled with the Herschel–Bulkley equation. FTIR spectroscopy was used to identify functional groups in the mucilage. The quadratic polynomial model reliably predicted mucilage yield (R^2 = 0.8673 and adjusted R^2 = 0.7578, $p<0.0001$). Extraction water ($p=0.0001$) and okra mass ($p=0.0294$) significantly influenced yield, while temperature showed no significant linear effect. Optimal extraction conditions were 619.3 mL of extraction water and 131.4 g of okra, at 80 °C, resulting in a predicted yield of 11.87%. Rheological analysis revealed a pseudoplastic, shear-thinning behavior (flow index $n=0.708$) with a moderate thickening capacity, suitable for suspension and gel formation. FTIR analysis confirmed polysaccharide composition with hydroxyl, carbonyl, ester, and β-glycosidic functional groups. TGA analysis confirmed that okra mucilage thermal stability is sufficient for most food processing involving moderate heat treatments. Okra mucilage demonstrates properties ideal for use as a natural thickener, emulsifier, binder, and gelling agent in the food industry, offering a reliable basis for its incorporation into functional formulations and innovative applications. FTIR and TGA analyses confirm that the extracted okra mucilage is chemically pure, structurally uniform, and free of significant protein or lipid contamination, making it suitable for food, pharmaceutical, and nutraceutical applications.

Highlights

- Optimised extraction used 619.3 mL of water and 131.4 g of okra at 80 °C.
- Crude okra mucilage showed pseudoplastic behaviour with moderate industrial thickening.
- FTIR confirmed hydroxyl, carboxyl, ester, β-glycosidic linkages, and amide II.
- TGA showed major mucilage thermal degradation onset above 150 °C.

Keywords Crude mucilage extract · Functional food ingredients · Plant-derived polysaccharides · Response surface methodology (RSM) · Rheological properties

✉ Frederick Tawi Tabit
tabitft@unisa.ac.za

Nelly Virginia Nkosi
nvmawandla@gmail.com

[1] Department of Life and Consumer Sciences, Corner of Christiaan de Wet and Pioneer Avenue, University of South Africa, Florida, Roodepoort 1710, South Africa

Introduction

Okra (*Abelmoschus esculentus*) mucilage is a naturally occurring, water-soluble polysaccharide that can be extracted from fresh fruit pods [1]. Due to its non-toxic nature and favourable physicochemical and functional properties, including biodegradability, film-forming capacity, and antioxidant/antimicrobial activity, mucilage has attracted interest for both food and non-food applications [2]. The increasing interest in plant-derived mucilage as a substitute for synthetic polymers stems from its natural abundance, biodegradability, safety, non-toxicity, and low extraction and processing costs. Additionally, it is an accessible, eco-friendly, and functional alternative to petroleum-based polymers in contemporary food systems [3]. Consequently, food manufacturers are progressively replacing synthetic emulsifiers with natural biopolymers such as cellulose, glucans, gums, and mucilage to meet sustainability goals and consumer demand for safer, naturally derived products [4]. Mucilage has been widely reported as a functional ingredient in the food and pharmaceutical industries, particularly noted for its ability to serve as a thickener, binder, gelling agent, film former, emulsifier, and stabiliser due to its favourable physicochemical properties [5]. For example, taro (*Colocasia esculenta*) mucilage exhibited high emulsion activity (79.54%) and stability (95.83%), supporting its application as a natural emulsifier [6]. Similarly, okra mucilage has been shown to enhance stability in pistachio nut paste by 80.80% [7] and improve the quality of gluten-free chiffon cake [8], as well as reduce-fat emulsions like mayonnaise [9].

Natural biopolymers have gained significant attention in food preservation due to their biodegradability, film-forming ability, and potential to carry functional additives such as antioxidants. In this regard, okra mucilage, a polysaccharide-rich extract, represents a promising candidate for such applications, offering both rheological functionality and potential as a carrier of bioactive food ingredients [10]. Okra mucilage has the potential to be used as a natural food additive or coating agent, providing functional properties relevant in food processing, especially concerning the increasing demand for environmentally friendly food additives. Edible coatings based on plant-derived mucilages, such as okra mucilage, can enhance the safety and stability of food products by forming a protective barrier that slows microbial and fungal growth [11]. This barrier can help inhibit contamination by fungi that produce harmful mycotoxins, such as Aflatoxin M1 in dairy products, while also regulating moisture and oxygen transfer. Combined with potential antimicrobial or antioxidant compounds, okra mucilage coatings offer a natural and sustainable approach to extending shelf life and improving food quality [12]. Plant-derived mucilages, such as sage seed gum and okra mucilage, can be used in nanoemulsion-based coatings to extend the shelf life of fresh produce by reducing microbial spoilage and slowing the quality deterioration of agricultural products [13].

The Okra plant is an important yet under-researched and under-utilised crop in South Africa [14], mainly cultivated in warm subtropical regions, including Limpopo, KwaZulu-Natal, the Mpumalanga Lowveld, Northwest, and irrigated areas of the Northern Cape [15]. These regions are characterised by high summer temperatures (25–35 °C), 600–1200 mm of summer-dominant rainfall, and sandy-loam soils (pH 6–7), which favour vigorous okra growth [16]. Elevated temperatures and solar radiation enhance polysaccharide biosynthesis, resulting in mucilage with higher viscosity and yield [17]. Adequate soil moisture promotes mucilage solubility and molecular weight, whereas drought stress, common in semi-arid regions, leads to more fibrous pods with reduced hydration capacity [18]. In addition, enhancing drought and salinity tolerance in okra (*A. esculentus*) is essential to sustain mucilage yield, as climate-induced water scarcity and soil salinisation disrupt physiological processes, reducing pod development, fruit quality, and overall productivity [19].

Mucilage is a viscous, water-soluble polysaccharide typically composed of repeating rhamnose and galacturonic acid units, with galactose side chains contributing to its functional properties [20]. Mucilages are particularly noted for their ability to rapidly absorb water, forming a mucilaginous layer, and their compatibility with food systems makes them an attractive choice, safer for consumption than synthetic additives [13]. Okra mucilage is a chemically inert, anionic polysaccharide rich in polyhydroxy and carboxylated groups, conferring water solubility and the ability to form stable hydrogels with desirable plasticity, elasticity, and viscosity for food and pharmaceutical applications [21]. Mucilage extraction has been carried out using two principal approaches. In the conventional method, plant material is first homogenised and subjected to hot water extraction to solubilise the mucilage, after which the extract is filtered or centrifuged to remove insoluble residues. The clarified aqueous extract is then precipitated with ethanol, reducing polysaccharide solubility and allowing mucilage recovery, followed by washing to remove impurities and drying for subsequent analysis or application. Alternatively, dried plant material may be ground into a fine powder and dispersed in water, filtered, and subjected to freeze–thaw treatment (FTT) to enhance cell wall disruption and polysaccharide release. The resulting extract is centrifuged at 4,000–6,000 × g for 15–20

min to remove precipitated proteins and insoluble matter, and the mucilage is finally recovered by ethanol precipitation [22, 23]. Although alkaline conditions often enhance yield compared to acidic media [24], challenges remain regarding consistent bioactivity, structural characterisation, and scalability [25]. Consequently, optimising extraction conditions is critical, and response surface methodology (RSM) provides an effective approach for defining relationships among extraction variables [26]. This study, therefore, optimised the aqueous extraction of crude okra mucilage to obtain minimally impure extracts suitable for food processing and evaluated their functional and structural properties using rheological analysis, FTIR, and TGA.

Materials and methods

Collection and preparation of okra fruits

Fresh okra (*Abelmoschus esculentus* (L.) fruits, 5 kg) was obtained from SwaTsakani Farm, Tzaneen, Limpopo, South Africa, and stored at 5 °C until processing. The crop was cultivated during the summer season (January–February) under average conditions of 27 °C, 165 mm monthly rainfall, and 75% relative humidity [27]. The pods were washed with distilled water, seeds and calyces removed, and the fruits sliced into uniform pieces (10 × 14 cm).

Extraction of mucilage from okra fruits

All chemicals were obtained from Merck (Modderfontein, South Africa), and deionised water (Milli-Q, Millipore, Gauteng, South Africa) was used throughout. Sliced okra samples were mixed with deionised water and blended at ~19,000 rpm for 3 min (Philips Series 3000 ProBlend 4). The slurry was heated at 65–95 °C for 90 min with continuous stirring, then centrifuged at 10,000 × g for 10 min (Beckman Coulter Avanti J-26 S XPI) to remove pulp and fibres. Mucilage in the supernatant was precipitated with 95% (v/v) food-grade ethanol, washed twice with 50% ethanol, and reprecipitated with 95% ethanol until clear. The precipitate was freeze-dried at −56 °C for 24 h (HRC100, Harvest Right, USA), weighed, and the mucilage yield (%) was calculated (Eq. 1).

$$\%Yield = \frac{Weight\ of\ freeze\ dried\ mucilage(g)}{Weight\ of\ raw\ okra\ fruits\ (g)} \times 100 \quad (1)$$

Experimental design

A Central Composite Design (CCD) (Table 1) was applied using Design-Expert® version 11.0.0 to optimise mucilage extraction. Extraction temperature (X_1), okra material amount (X_2), and extraction water volume (X_3) were

Table 1 The central composite design (CCC) of experimental runs and corresponding response data for input factors

Run	Factor 1	Factor 2	Factor 3	Response 1	Response 2
	X1: Amount of extraction water	X2: Amount of Okra	X3: Extraction temperature	Y: Actual okra Mucilage yield	Y: Predicted okra Mucilage yield
	(mL)	(g)	(°C)	%	%
1	619.314	100	80	9.847(±0.299)	10.27
2	325	100	46.3641	3.227(±0.844)	4.42
3	150	150	100	1.638(±0.334)	2.11
4	325	100	80	3.999(±0.312)	4.44
5	325	100	113.636	5.936(±0.357)	6.44
6	325	184.09	80	2.850(±0.750)	3.91
7	325	100	80	4.589(±0.105)	4.44
8	150	50	60	2.084(±0.259)	2.45
9	500	50	100	7.095(±0.718)	8.11
10	500	150	100	11.874(±0.106)	10.31
11	325	100	80	4.58(±0.384)	4.44
12	325	100	80	4.589(±0.446)	4.44
13	325	100	80	4.590(±0.187)	4.44
14	30.6863	100	80	1.090(±0.563)	2.36
15	500	150	60	5.527(±0.384)	6.07
16	325	15.9104	80	0.112 ((±0.446)	0.6309
17	500	50	60	5.338(±0.187)	3.66
18	150	150	60	6.37(±0.563)	4.16
19	325	100	80	4.585(±0.103)	4.44
20	150	50	100	2.357(±0.231)	0.6160

selected as independent variables, with mucilage yield (Y) as the response. The design comprised factorial, axial, and centre points, with variables coded at five levels (−α, −1, 0, +1, +α) to ensure rotatability and enable estimation of linear, interaction, and quadratic effects. A quadratic model was developed and evaluated by ANOVA, and model validity was confirmed by comparing predicted and experimental yields using regression analysis and correlation coefficients.

Measurement of the rheological properties of okra mucilage

Rheological properties were measured following the method of [28] using an RST-SST Touch Rheometer (Massachusetts, USA) equipped with a vane spindle (CCT-25) and connected to a water bath. A 1% (w/w) okra mucilage solution was prepared in deionised water, stirred slowly at room temperature, and hydrated at 4 °C for 24 h. Measurements were conducted at 25 °C, over a shear rate range of 0.01–1000 s^{-1} using the controlled rate mode. Shear stress, shear rate, and viscosity data were recorded and analysed with Brookfield Rheo3000 software and fitted to the Herschel–Bulkley model (Eq. 2) to determine the consistency index (K), flow behaviour index (n), and yield stress (τ_0).

$$\tau = \tau_o + K(\dot{\gamma})n \tag{2}$$

Fourier transform infrared (FTIR) and thermogravimetric analysis (TGA) of okra mucilage

FTIR was used to identify functional groups in freeze-dried okra mucilage with a Bruker VERTEX 70 spectrometer and ATR (400–4000 cm^{-1}, 4 cm^{-1} resolution, 32 scans), following Alpizar-Reyes et al. [29]. Samples were applied directly to the ATR crystal and analyzed in triplicate. Thermal stability was evaluated by TGA using a TGA-DSC SDT Q600 under nitrogen flow (100 mL/min); 5–8 mg of mucilage was heated from 20 to 1000 °C at 10 °C/min, with weight loss and DTG recorded to determine moisture loss and degradation temperatures [30].

Results

Statistical considerations

The terms in the function were considered significant at $p<0.05$, and regression coefficients (R^2) greater than 0.70 were considered a good fit for the model. The R^2 measures the amount of variation around the mean as explained by the model. The polynomial model was relevant in the prediction of mucilage yield with a coefficient of determination (R^2) and adjusted coefficient (Adj. R^2) of 0.8673 and 0.7578, respectively. The regression coefficient for the linear and quadratic terms in the model has been expressed in the regression equation (Eq. 3).

$$\begin{gathered} Y(\%) = 12.4335 - 0.0385345X_1 + 0.0784845X_2 - \\ 0.250398X_3 + (2.00143 \times 10^{-5})X_1X_2 + \\ (0.000448679)X_1X_3 \\ -(5.1875 \times 10^{-5})X_2X_3 + (2.16542 \times 10^{-5})X_{1^2} - \\ (0.000306609)X_{2^2} + (0.000873671)X_{3^2} \end{gathered} \tag{3}$$

The effect of extraction parameters on okra fruit mucilage yield

The quadratic model results for okra mucilage yield indicate that both the amount of extraction water (X1) and the amount of okra (X2) exert significant positive effects on yield, as shown by their low p-values ($p=0.0001$ and $p=0.0294$, respectively). The interaction between extraction water and temperature (X1 × 3) is also significant ($p=0.0107$), suggesting that extraction temperature modulates the effect of water on yield. The quadratic term for the amount of okra ($X2^2$) is marginally significant ($p=0.0676$), implying a potential non-linear relationship in which further increases in okra may not always result in proportional increases in yield. Other variables, including extraction temperature alone (X3), the interaction terms X1 × 2 and X2 × 3, and the quadratic terms $X1^2$ and $X3^2$, were not statistically significant (Fig. 1).

Figure 2 illustrates a significant interaction between extraction water and temperature (X1 × X3), where simultaneous increases in both factors enhance mucilage yield. While interactions between okra amount and extraction water (X1 × 2) (Fig. 3) and okra amount and extraction temperature (X2 × 3) (Fig. 4) were not significant, increasing both factors still enhanced yield. Overall, the 3D plots highlight the critical role of extraction temperature in the extraction of mucilage. The relationship between extraction yield and independent variables of extraction water, the amount of okra, and extraction temperature in terms of coded variables is given in Eq. 2.

Linear regression of the actual and predicted mucilage extraction yield

The scatter plot of actual versus predicted okra mucilage yield demonstrates a strong positive relationship, with most points closely aligned to the regression line ($y=0.868x+0.61$). The high R^2 value of 0.867 (Fig. 5) closely matched the 0.8673 obtained from the RSM model, indicating strong predictive accuracy of the regression model (Table 2).

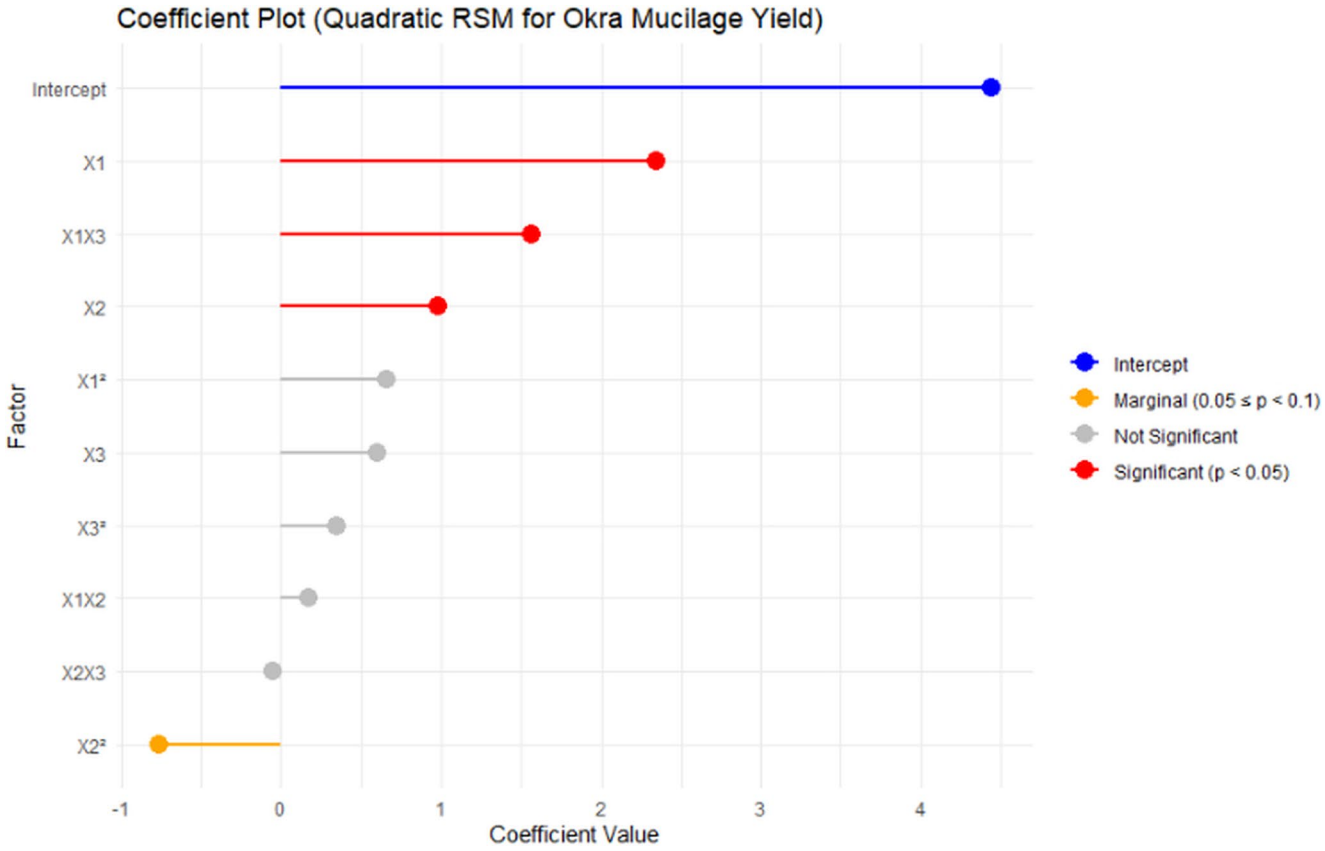


Fig. 1 Coefficients for the quadratic response surface model of okra mucilage extraction yield

Predicted optimal condition

The 2D desirability plot shows how varying the amount of extraction water (0–700 mL) and okra (20–180 g) at 80 °C affects the process desirability. The optimum extraction conditions for mucilage are clearly marked at 619.3 mL of water and 131.4 g of okra, where the desirability reaches its maximum value of 1. The mucilage yield, as determined from experimental validation, was 13.679%. The contour lines and colour gradient illustrate that desirability increases as both water and okra amounts approach these optimal values, helping to identify the best combination for the process visually. (Fig. 6).

Rheological properties of okra mucilage

The viscosity diagram shows that as shear rate increases, the viscosity of the sample (blue circles) decreases sharply from about 350 mPa·s at low shear rates and then levels off below 50 mPa·s at higher shear rates, indicating shear-thinning (pseudoplastic) behaviour. In contrast, the temperature (red triangles) remains constant at approximately 250 mPa·s across all shear rates, serving as a reference. This demonstrates that the sample's viscosity is highly dependent on shear rate, decreasing significantly as shear rate increases (Fig. 7). The flow behaviour of the mucilage solution was effectively described using the Power Law–Herschel-Bulkley model. The flow behaviour index (n) was 0.708, confirming its shear-thinning nature, while the consistency coefficient (K) was 0.2777, indicating moderate thickening capability (Table 3).

FTIR spectroscopic characterisation of Okra mucilage

The FTIR spectrum for okra mucilage displays characteristic peaks at 3269 cm^{-1} (O-H), 2914 cm^{-1} (C-H), 1720 cm^{-1} (C=O), 1596 cm^{-1} (-COO), 1190 cm^{-1} (C-O), and 890 cm^{-1} (C=C), indicating the presence of hydroxyl, alkyl, carbonyl, carboxylate, ether, and alkene functional groups. This confirms the complex molecular structure and diverse chemical functionalities present in okra mucilage (Fig. 8).

Thermogravimetric analysis (TGA) characterisation of okra mucilage

Thermogravimetric analysis of okra mucilage revealed a multistep weight loss typical of natural polysaccharides.

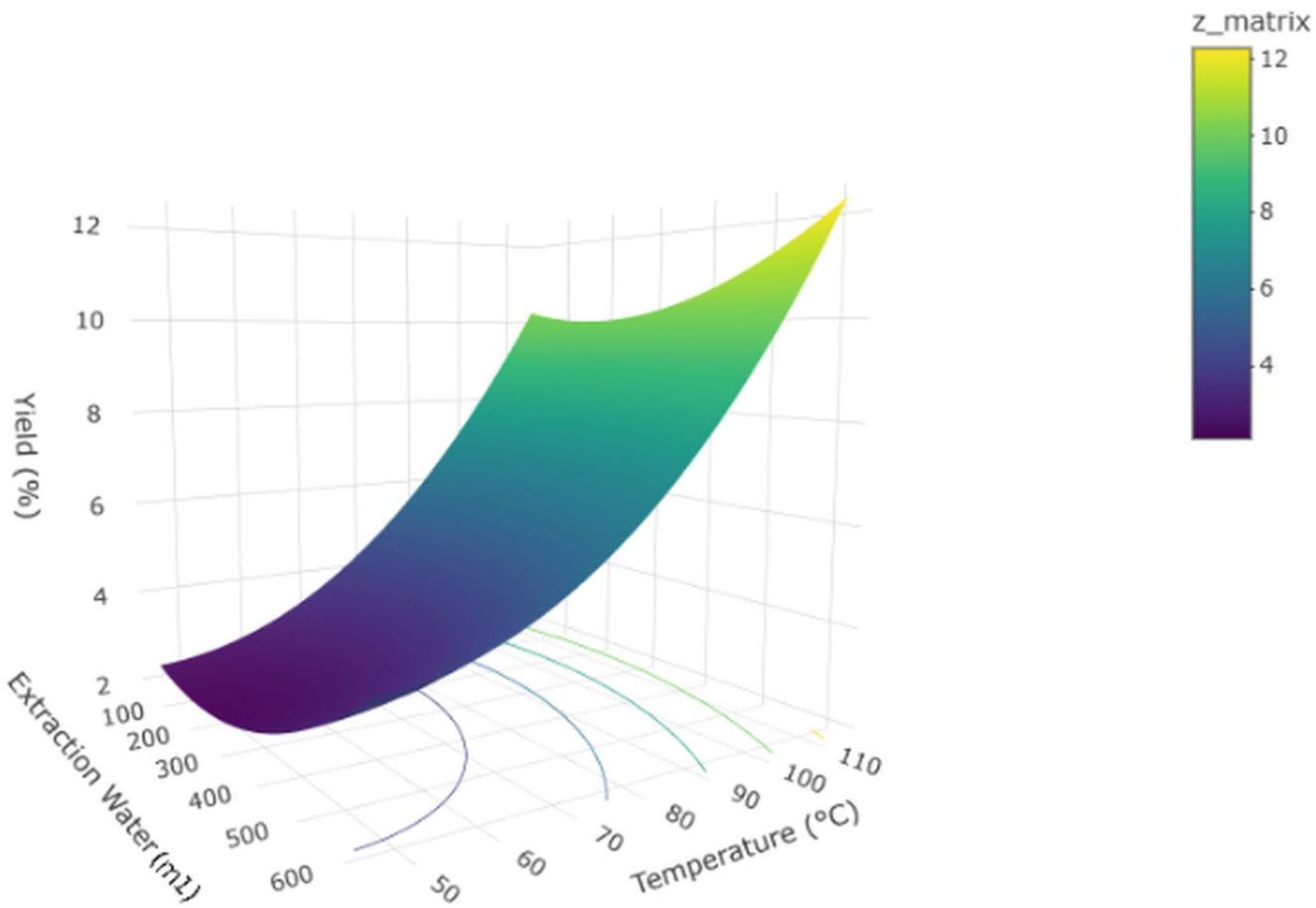


Fig. 2 A 3D graph showing the effect of the amount of extraction water (mL) and the extraction temperature (°C) on mucilage yield at a fixed amount of okra material at 100 g

Initial loss below 100 °C (DTG ~82.35 °C) corresponds to adsorbed moisture, while 120–200 °C (DTG ~156.70 °C) reflects bound water loss and side chain depolymerisation. Major decomposition occurred at 230–320 °C (DTG ~275.68 °C) due to glycosidic bond cleavage, followed by gradual mass loss above 350 °C from carbonisation and char formation, indicating thermally resistant components. (Fig. 9).

Discussion

Statistical considerations

The high R^2 (0.8673) and adjusted R^2 (0.7578), along with the statistical significance of the quadratic model ($p < 0.0001$), indicate that the model accurately captures the effects of extraction parameters on mucilage yield. In a study conducted on the optimisation of mucilage extraction from prickly pear (*Opuntia dilleniid*) fruits and quince seed (*Cydonia oblonga*), R^2 values of 0.97 and 0.98, respectively, were obtained, which was an indication of a good fit of the models used [31]. When the R^2 values exceed 0.8, it is an indication of a good fit and a better desirability of the model to predict the response variable [32, 33]. The closeness between the coefficient of determination (R^2) and the adjusted coefficient of determination (Adj. R^2) indicates the desirability of the model [34]. The significance of the quadratic model obtained implies that it can be effectively used to predict okra mucilage yield. Thus, the model utilised in this study is effective for optimising extraction conditions [35].

The model also highlights which parameters (notably extraction water and its interaction with temperature) are most critical, enabling process optimisation for consistent, high-quality mucilage extraction [36]. The significance of the extraction water and temperature is associated with the fact that water acts as a driving force, and temperature allows better penetration of the aqueous medium to increase yield, thus ensuring mass transfer during extraction, which was presumably the reason for the considerable dependency of mucilage yield on the water-to-raw material ratio [37].

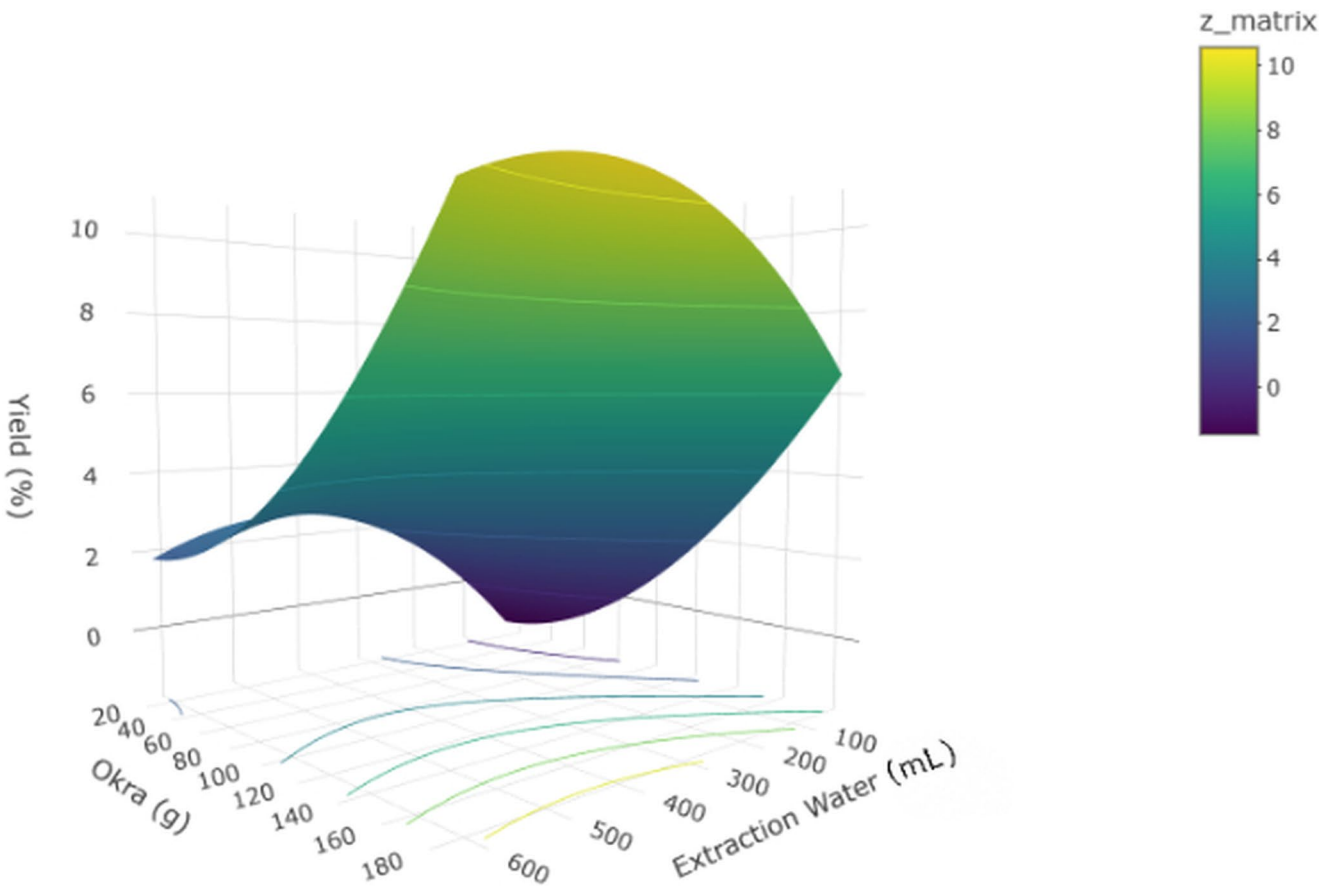


Fig. 3 A 3D graphic showing the effect of the amount of extraction water (mL) and the amount of okra (g) on mucilage yield at a fixed extraction temperature of 80 °C

The effect of extraction parameters on Okra fruit mucilage yield

In the polynomial model, only the linear terms X_1 (amount of extraction water, mL) and X_2 (amount of okra, g) significantly influenced mucilage yield. The coefficient analysis showed that the effect of the extraction water was approximately twice that of the okra amount (Table 2). These results highlight that okra mucilage is easily extracted in an aqueous medium because it is soluble in water; hence, this property makes water play a critical role during the extraction process to obtain viscous mucilage [38]. Similarly, a study on the extraction condition optimisation and effects of drying methods on physicochemical properties and antioxidant activities of polysaccharides from Astragalus cicer L. reported that the impact of water to raw material ratio on polysaccharide yield (*Astragalus cicer L*) significantly increased as water ratio increased ($P < 0.05$) [39]. While another study on optimisation of the extraction of mucilage from the seeds of *Mimosa pudica* by Response Surface Methodology. The seed-to-water ratio was reported to have a significant effect ($P < 0.0001$) on mucilage yield, relative to the extraction water volume, highlighting the critical role of water volume during extraction [40]. Water enhances solubility by dissolving the ground okra material, thereby increasing the yield of mucilage. A higher okra mass provides more material for extraction, and thus, the water amount/ratio is often the dominant factor among extraction conditions. This aligns with the idea that extraction water plays a critical role in mucilage recovery [36]. Extraction temperature alone was not linearly related to mucilage yield [41].

The interactive term X_1X_3 (extraction water × extraction temperature) significantly affected mucilage yield ($p \leq 0.05$), as shown in the 3D response surface plots, which demonstrated that this interaction produced the highest yields compared to other interactions [36]. Heated water enhances solubility and penetrates plant material more effectively, facilitating mucilage release [27]. In contrast, the interactions X_1X_2 and X_2X_3 did not significantly influence yield, indicating that interactions involving the amount of okra material have a minimal effect. This is likely because increasing okra mass does not substantially affect solubility, which is the primary factor controlling mucilage extraction

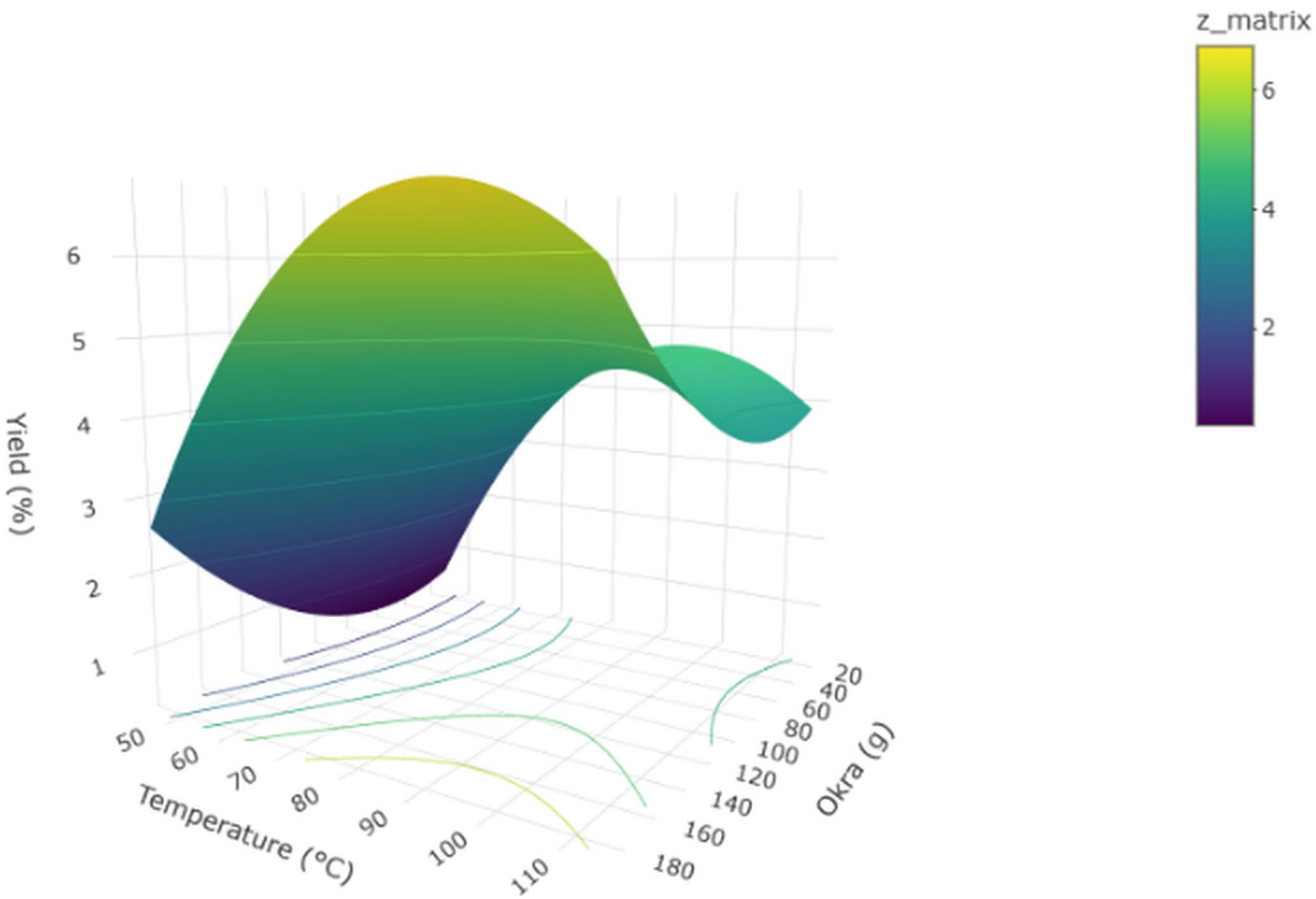


Fig. 4 A 3D graph showing the effect of the amount of okra (g) and the extraction temperature (°C) on mucilage yield at a fixed volume of extraction water at 325 mL

[29]. These results highlight that controlling the water-to-material ratio and applying heated extraction water are the most critical factors for maximising okra mucilage yield. The significance of water in ensuring mass transfer during extraction likely accounts for the considerable dependency of mucilage yield on the water-to-raw material ratio, with higher water-to-solid ratios generally increasing extraction efficiency by improving solubilisation of polysaccharides [42].

Optimization and validation of okra mucilage yield

Looking at the contour plots for optimum mucilage yield (Fig. 5), the optimal predicted yield was 11.874% with a desirability of 0.79 with the actual validated mucilage yield was 13.679%, which was not significantly different from the predicted value, with $R^2 = 0.87$ at $p < 0.001$, indicating that the extraction conditions derived from RSM are valid for okra mucilage extraction. These results suggest that optimal extraction conditions derived from RSM are valid for extracting mucilage from okra fruits. A previous study reported a relatively similar mucilage yield of 11.6% for chia seeds *(Salvia hispanica L.)* mucilage [43], which is similar to the maximum yield of 10.66% obtained from Mimosa pudica seeds in another study [40]. Therefore, the close agreement between actual and predicted mucilage yields confirms the reliability of the RSM model, demonstrating its suitability for guiding large-scale mucilage extraction.

Rheological properties of okra mucilage extracted under optimised conditions

Figure 6 illustrates the relationship between shear rate ($\dot{\gamma}$) and apparent viscosity (η) of 1% okra mucilage. The viscosity rapidly decreased with increasing shear rate from 0.01 to 1000 s^{-1}, demonstrating pseudoplastic (shear-thinning) behaviour [44]. A yield stress of 5.24 Pa was observed at the onset of shear. This shear-thinning behaviour is attributed to the alignment of polymer chains along the flow direction, reducing internal resistance [45]. Previous studies have shown that higher molecular weight polysaccharides exhibit stronger pseudoplasticity and higher viscosity [46]. Similar observations were reported for mucilage from *Opuntia*

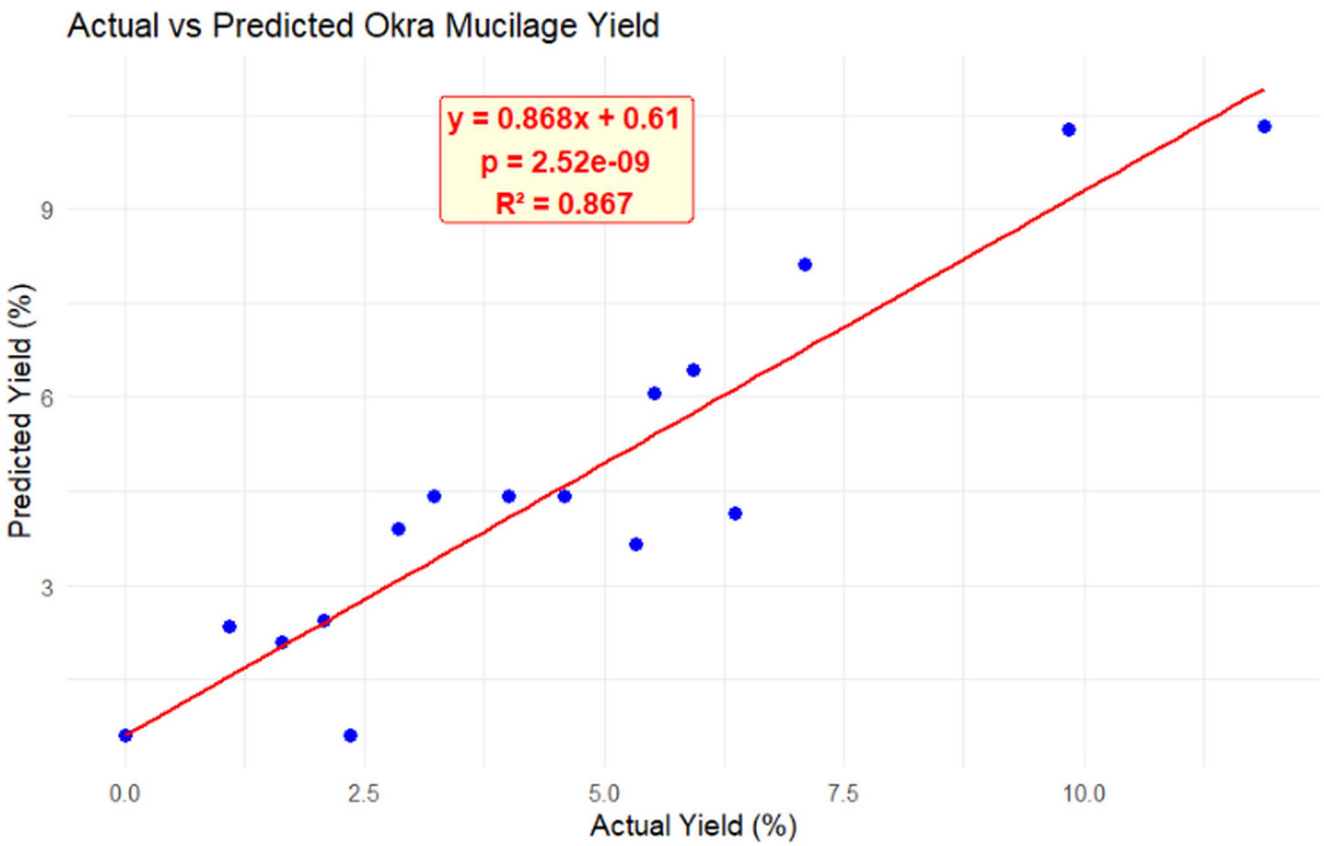


Fig. 5 The Linear regression of the actual mucilage extraction yields against the predicted mucilage extraction yield of the RSM experiment

Table 2 Analysis of variance (ANOVA) and model coefficients for the quadratic response surface model of Okra mucilage extraction yield

Factor	Coefficient terms	*P* values	Interpretation
Intercept	4.440		
X1	2.35	**0.0001***	**Significant (*)**
X2	0.9759	**0.0294***	**Significant (*)**
X3	0.6004	0.1492	Not significant
X1 × 2	0.1751	0.7345	Not significant
X1 × 3	1.57	**0.0107***	**Significant (*)**
X2 × 3	−0.0519	0.9198	Not significant
$X1^2$	0.6632	0.1067	Not significant
$X2^2$	−0.7665	**0.0676¥**	**Marginally significant (¥)**
$X3^2$	0.3495	0.3722	Not significant
R^2	0.8673		Explain how well the regression model fits the data.
Adjusted R^2	0.7578		Explain how well the regression model fits the data, considering the number of predictors.

p-values ≤ 0.05 are considered significant (*), **0.5 < p-values < 0.10, are considered marginally significant (¥)** and p-values ≥ 0.1, are considered insignificant. X1 = Amount of extraction water, X2 = Amount of okra and X3 = extraction temperature

cladodes [47]. Additionally, mayonnaise samples formulated with sesame seed protein isolate exhibited shear-thinning behaviour, showing a decrease in viscosity with increasing shear rate [9]. Such shear-thinning hydrocolloids are valuable in food applications as viscosity modifiers and thickening agents [48]. The significance of mucilage viscosity in this study may be an important indicator for developing body and mouth feel in food processing and production [49].

The flow behaviour of okra mucilage was effectively modelled using the Power Law–Herschel-Bulkley model. The flow behaviour index (n = 0.708) confirmed its shear-thinning nature, with n decreasing at higher shear rates, indicating more pronounced pseudoplastic behaviour. Low n values signify a substantial departure from Newtonian flow, with high viscosity at low shear rates that decreases under stress, useful for suspending particles or forming gels in foods and pharmaceuticals [50]. Similarly, shear-thinning behaviour was observed in polysaccharides from Colocasia esculenta *and* Opuntia spp., as well as other okra mucilage solutions [51]. The consistency index (K = 0.2777) indicated moderate thickening capability, reflecting intermolecular interactions and entanglement within the mucilage solution [52]. Increasing mucilage concentration correspondingly

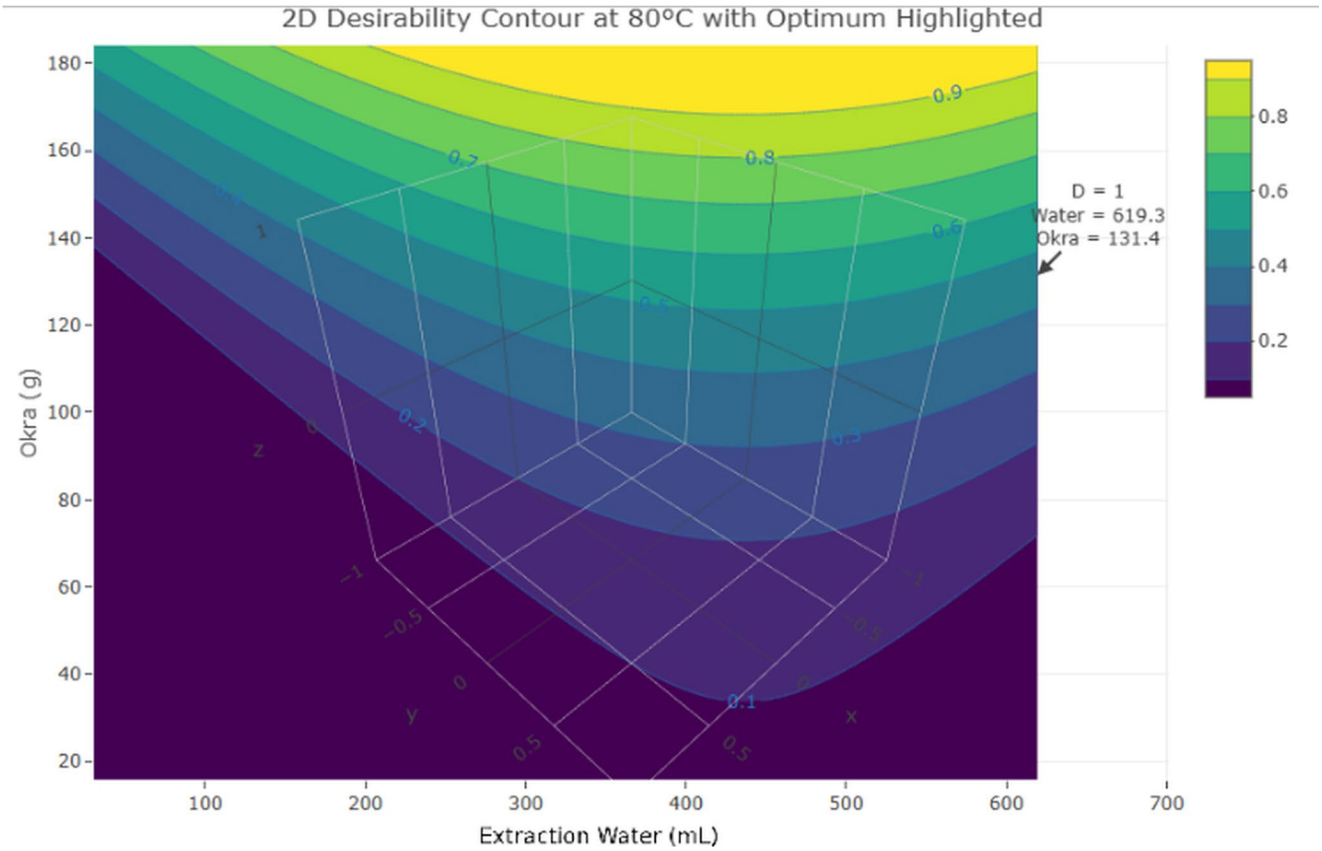


Fig. 6 Desirability contour plots for optimum mucilage yield extraction conditions for water and amount of okra at 60˚C

increased viscosity, consistent with studies on mucilage-CMC blends in mango nectar, where K values ranged from 0.20 to 0.49, depending on the stabilizer concentration [53].

FTIR spectroscopic characterisation of okra mucilage

FTIR spectra of the extracted okra mucilage displayed characteristic peaks of polysaccharides, with variations in peak intensities indicating differences in functional group contents. Six distinct functional groups were identified: hydroxyl groups (O–H, 3240 cm^{-1}), alkyl chains (C–H, 2914 cm^{-1}), carbonyl groups (COO, 1719 and 1596 cm^{-1}), carboxylic ester groups (1720 and 1500 cm^{-1}), C–O–C and C–OH groups (1190 cm^{-1}), and the β-glycosidic linkage fingerprint region (~ 890 cm^{-1}) as illustrated in Fig. 7.

The absorption band at 3415–3276 cm^{-1} corresponds to O–H stretching vibrations and hydrogen bonding, representing hydroxyl groups of polysaccharides such as rhamnose, galacturonic acid, and galactose [45, 46]. These bands reflect the complex vibrational patterns of free and bound hydroxyl groups in okra mucilage, which facilitate extensive hydrogen bonding, contributing to their high water-holding capacity and functionality as emulsifiers or stabilisers in food systems [47]. Typical mucilage peak at 2914 cm^{-1} is attributed to C–H stretching, associated with the fundamental carbohydrate structure The sharp peaks between 1719 and 1596 cm^{-1} indicate the presence of carbonyl –COO groups, which support emulsifying and film-forming properties and confirm the presence of uronic acids [54]. In addition, uronic acids are usually present in seed gums, imparting an anionic character to the molecular structure [55].

The 1720–1500 cm^{-1} region represents carboxylic acid and ester groups, enabling the assessment of the esterification degree; the 1720 cm^{-1} peak corresponds to ester carbonyl groups, consistent with previous studies on okra mucilage [56]. The presence of carboxylic and ester groups can serve as a site for ionic bonds, which can have significant effects on functional properties of mucilage, such as gel formation and viscosity [55]. For instance, the band observed at 1580 cm^{-1} corresponds to the characteristic amide II band associated with the vibrations related to the -NH3 + groups, and it reflects the presence of proteinaceous residues, which improve foaming, film formation, and emulsion stability of mucilage [57]. The band at 1190 cm^{-1} arises from C–O–C and C–OH vibrations [58, 59]. The 890 cm^{-1} peak represents β-glycosidic linkages between sugar polysaccharides,

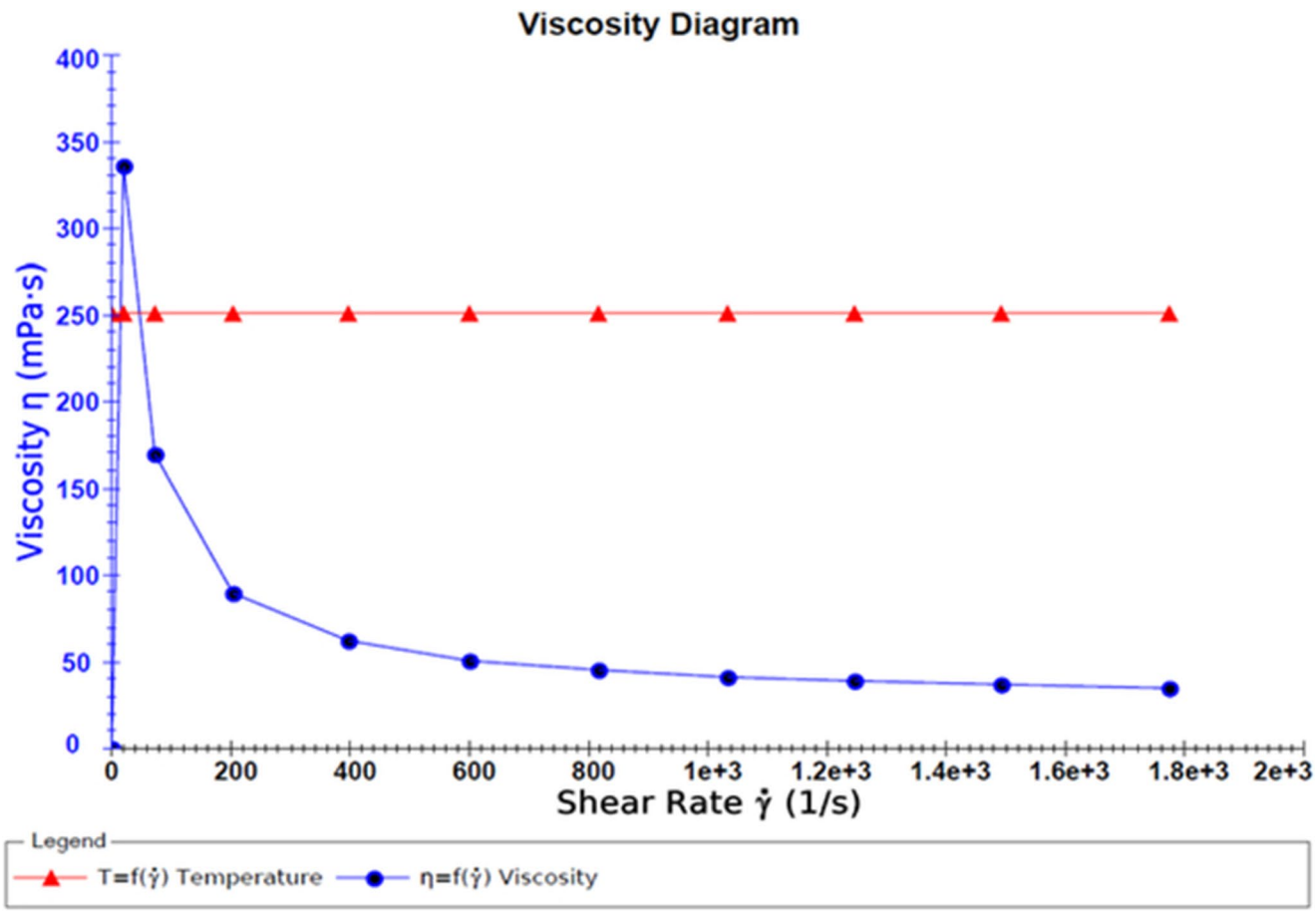


Fig. 7 The viscosity diagram of okra mucilage extracted under optimised conditions as a function of shear rate at 25 °C

Table 3 Okra mucilage flow behaviour index characterisation as estimated by Herschel-Bulkley regression model

Okra Mucilage Concentration (% w/v)	Flow Behavior Index, *n*	Consistency Index, K (Pa·s^n)	Viscosity (mPa·s)
1	0.708	0.277	335.76 mPa·s

which impart viscosity and thickening ability of mucilage [60]. The presence of carboxyl and hydroxyl functional groups in okra mucilage is characteristic of polysaccharide molecules and contributes to its biological activities, including antioxidant potential, cholesterol binding, and prebiotic effects [56]. The β-glycosidic linkages confirm the polysaccharide backbone of okra mucilage, a characteristic feature of polysaccharides that imparts viscosity, thickening ability, and rheological stability, thereby indicating the presence of carbohydrates in the sample [49]. Therefore, it is evident that the okra mucilage peaks observed in Fig. 7 agree well with previous reports, indicating that the mucilage is mainly composed of a water-soluble polysaccharide complex, mainly containing galactose, rhamnose, and galacturonic acid, vegetable proteins, and minerals [61]. The FTIR chemical characterisation of okra mucilage explains its emerging application as a natural thickener, stabiliser, and functional ingredient in food processing [47]. The FTIR characterisation of okra mucilage reveals spectra dominated by characteristic polysaccharide functional groups (hydroxyl, carboxyl, and glycosidic bonds), with no evidence of new peaks or significant contamination, confirming retention of its chemical identity and supporting its functionality as a natural thickener, stabiliser, and food ingredient [62].

Thermal behaviour and stability of okra mucilage

The initial weight loss of mucilage observed below 100 °C, with a DTG peak near 82 °C, is primarily due to the evaporation of physically adsorbed and weakly bound water molecules. This stage occurs before any structural decomposition and reflects the strong hygroscopic nature of mucilage, which readily absorbs moisture from its environment. Similar thermal profiles have been reported for plant-based polysaccharides such as okra and chia mucilage, where TGA/DTG analyses consistently show an early mass-loss

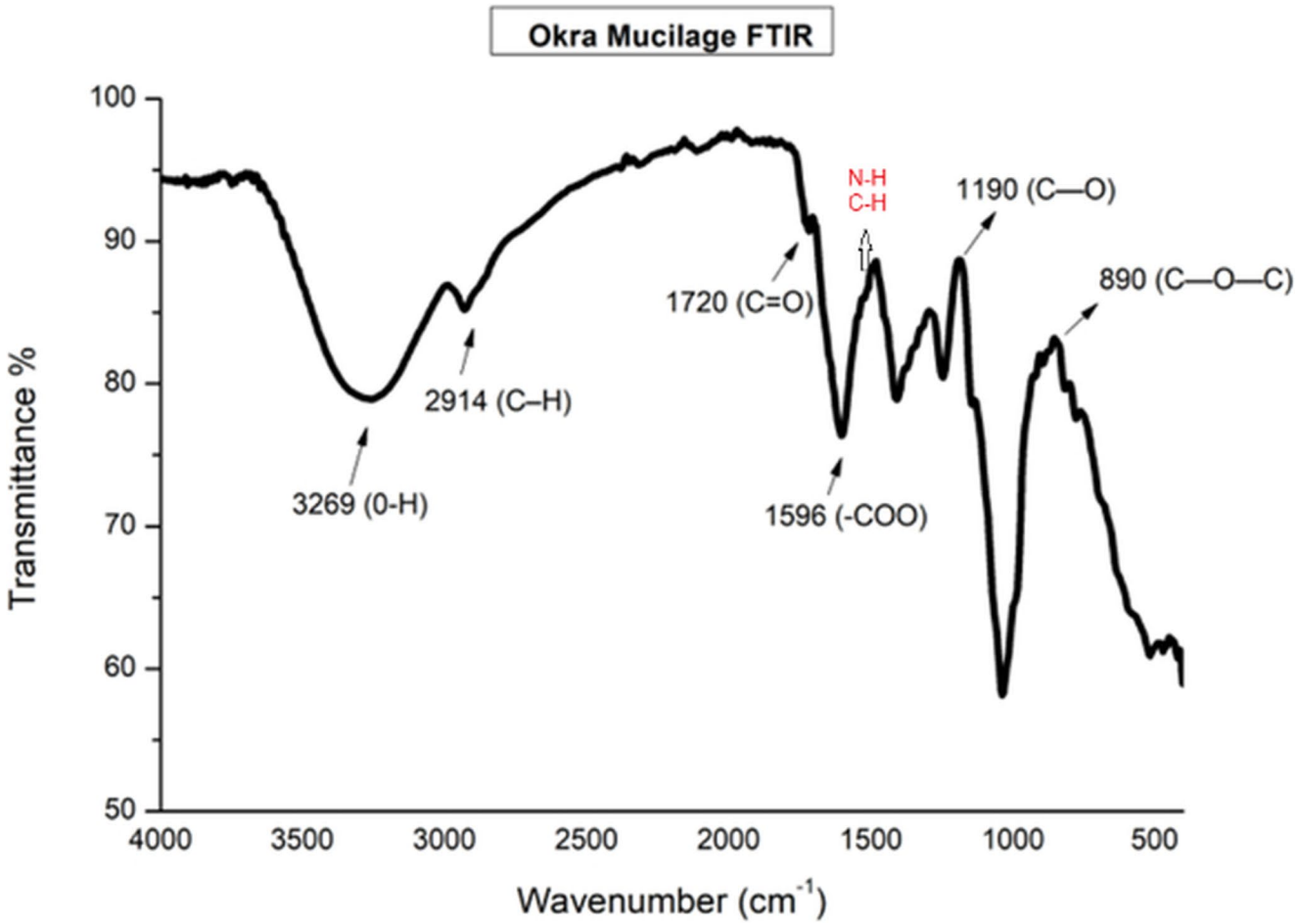


Fig. 8 FTIR spectrum of okra mucilage, highlighting the dominant functional groups

step below 100 °C attributed to moisture desorption, followed by major degradation at higher temperatures typically above 240 °C [63]. The hygroscopic nature of these biopolymers has been confirmed by reports of similar moisture evaporation temperatures for okra mucilage, chia mucilage, and basil seed gum [64]. The small mean loss up to 150 °C results indicate good thermal resistance of okra mucilage, which can be attributed to the highly branched RG-I structure of okra mucilage [65].

The second degradation stage was observed between 120 and 200 °C, corresponding to a DTG peak at approximately 156.7 °C, which signifies the release of more strongly bound water and the onset of depolymerisation of side chains. In this temperature range, water molecules are progressively liberated from tightly coordinated hydroxyl and carboxyl functional groups within the polysaccharide matrix, while increasing thermal energy initiates the cleavage of thermally labile side substituents, such as acetyl groups or pendant sugar residues. This stage, therefore, represents a transition from simple moisture loss to early chemical decomposition of the mucilage structure [66, 67]. This indicates that the okra mucilage structure can withstand processing temperatures well above typical cooking ranges; for instance, it may be utilised by food industries to optimise or retain acceptable thermal properties while offering far better throughput and reducing energy. Results also highlight that okra mucilage has higher thermal stability compared to other biopolymers, such as starch [68].

The principal thermal degradation of mucilage, occurring between 230 and 320 °C with a DTG peak around 275.7 °C, signifies the cleavage of glycosidic linkages and breakdown of the main polysaccharide chains, marking the material's thermal stability limit. Above this temperature, the polymer backbone undergoes rapid depolymerisation, releasing low-molecular-weight volatiles and resulting in substantial mass loss in the TGA curve. Subsequent gradual mass loss beyond 350 °C reflects carbonisation and char formation, indicating the presence of thermally resistant residual components. Similar findings were reported in a 2024 thermogravimetric study of okra and *Gracilaria corticata* in which a comparable main decomposition event around this temperature

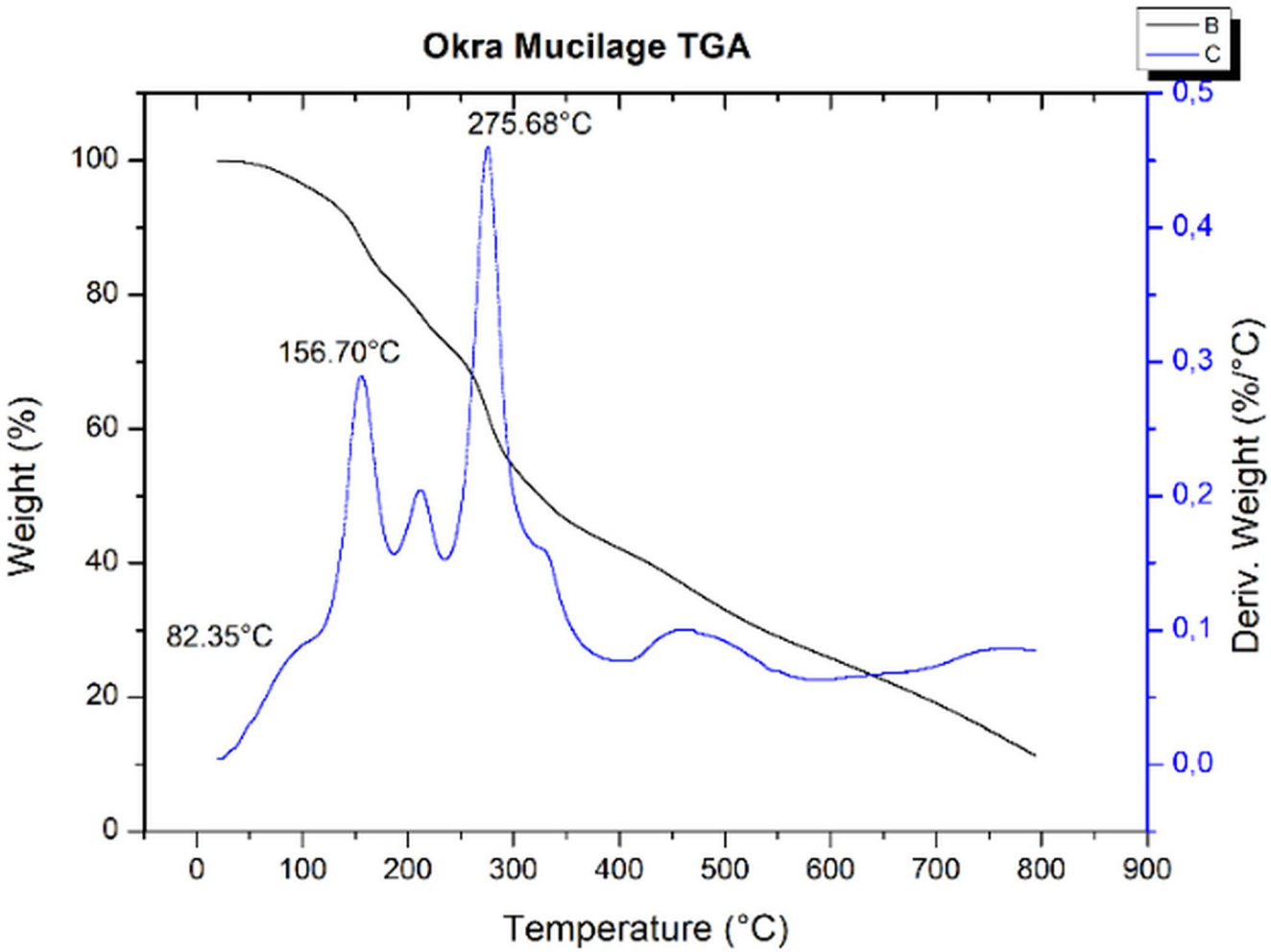


Fig. 9 Thermogravimetric analysis (TGA) spectrum and derivative thermogravimetry (DTG) profile of okra mucilage

range defined the onset of char formation and the limit of polysaccharide stability [69].

The significance of this result regarding mucilage purity is evident from the distinct thermal decomposition pattern. The major degradation stage, occurring between 230 and 320 °C, with a DTG peak at 275.7 °C, reflects the predominance of polysaccharide chains and minimal interference from non-polysaccharide impurities. Pure mucilage typically exhibits a sharp, well-defined decomposition event linked to glycosidic bond cleavage. In contrast, impurities such as proteins, lipids, or inorganic matter would cause overlapping degradation steps or alter the thermal profile. The gradual mass loss beyond 350 °C and residual char formation indicate minor mineral content and thermally stable fractions, which are common in natural gums but should remain low for high-purity samples. Overall, the observed thermal stability and decomposition stages confirm that the mucilage analysed is largely pure, consistent with profiles reported for mucilage from okra and other plants [70]. The assessment of mucilage purity can be effectively enhanced using complementary advanced analytical techniques. Fluorescence-sensing molecularly imprinted membranes constructed from hydrophilic–hydrophobic multifunctional monomers provide selective recognition of common co-extracted impurities such as endotoxins, proteins, and phenolic compounds, generating a measurable fluorescence response that correlates with contaminant concentration [71]. Meanwhile, a voltammetric sensor based on shuttle-shaped α-Fe_2O_3 nanoparticles decorated on multi-walled carbon nanotubes offers high sensitivity and electrochemical selectivity for trace electroactive impurities, with minimal interference from the largely inert polysaccharide matrix. Together, these methods enable rapid, non-destructive, and quantitative evaluation of mucilage purity, allowing clear differentiation between high-purity and contaminated samples. The combination of fluorescence and electrochemical detection provides a versatile and complementary platform for routine quality control, ensuring reliable standardisation of mucilage for food, pharmaceutical, and biomedical applications [72].

Thermally stable mucilage exhibits strong potential across agricultural, food, pharmaceutical, and biomedical systems owing to its film-forming ability, rheological stability, and compatibility with bioactive compounds. In agriculture, mucilage-based coatings mitigate moisture loss, oxidation, and microbial spoilage under variable temperature conditions, as demonstrated for antioxidant and edible carbohydrate films [10, 11]. Mucilage can also function as a stable carrier for antimicrobial agents, protecting heat-sensitive essential oils and enabling controlled release in nanoemulsion-based coatings [13]. In food processing, its thermal resilience supports application as a stabiliser or fat replacer in emulsified products subjected to pasteurisation and hot filling [9]. Similarly, in pharmaceutical and biomedical contexts, thermally robust mucilage enables drug-loaded films, controlled-release matrices, and sterilised biodegradable dressings, aligning with the functional requirements of polysaccharide-based materials [73].

Conclusions

Response Surface Methodology (RSM) was employed to optimise okra mucilage extraction, yielding a highly reliable model ($R^2 = 0.8673$, adjusted $R^2 = 0.7578$, $p < 0.0001$). The analysis identified the amount of extraction water and its interaction with temperature as the most influential factors, whereas temperature alone had minimal impact. Optimal conditions were 619.3 mL of water, 131.4 g of okra, at 80 °C. The validated model accurately predicts mucilage yield, highlighting the critical role of water in solubilising polysaccharides and facilitating mass transfer. These findings provide a basis for industrial-scale extraction, enabling consistent, high-quality mucilage production for use as a natural thickener, stabiliser, or functional ingredient in diverse food applications.

Extraction of okra mucilage is strongly influenced by the water-to-material ratio and the use of heated water, which enhances solubility and facilitates mass transfer. The amount of okra material has a lesser effect, and extraction temperature alone is not a significant factor. Optimisation via Response Surface Methodology (RSM) predicted a mucilage yield of 11.87%, which closely matched the validated yield of 13.68% ($R^2 = 0.87$, $p < 0.001$), confirming the reliability of the model for guiding extraction. To maximize okra mucilage yield in industrial applications, water volume should be carefully controlled, and heated water should be used to improve extraction efficiency. The validated RSM conditions can be adopted for large-scale production, providing a consistent, high-quality mucilage suitable as a natural thickener, stabilizer, or functional ingredient in food formulations.

The rheological analysis of 1% okra mucilage demonstrated pseudoplastic (shear-thinning) behaviour with a yield stress of 5.24 Pa and a flow behaviour index ($n = 0.708$), confirming non-Newtonian flow. The moderate consistency index ($K = 0.278$) reflects its thickening potential and intermolecular entanglements. Shear-thinning behaviour allows high viscosity at low shear rates and reduced resistance under stress, making okra mucilage suitable for suspending particles, forming gels, and modifying texture in food systems. Okra mucilage can be used as a natural thickener, stabiliser, or viscosity modifier in beverages, sauces, dressings, and other processed foods. Its pseudoplasticity enhances mouthfeel, enables uniform mixing, improves suspension stability, and facilitates energy-efficient pumping and processing during manufacturing.

FTIR analysis confirmed that okra mucilage is predominantly a water-soluble polysaccharide complex containing galactose, rhamnose, galacturonic acid, minor proteins, and minerals, with characteristic hydroxyl, carboxyl, ester, and β-glycosidic linkages. TGA revealed a multistage thermal profile: moisture loss below 100 °C, sidechain depolymerisation between 120 and 200 °C, and main polysaccharide degradation at 230–320 °C, with residual carbonisation above 350 °C. The distinct degradation stages indicate high thermal stability and purity, with minimal interference from impurities. Okra mucilage's functional groups and thermal resilience make it suitable as a natural thickener, stabiliser, gelling agent, and emulsifier in food systems. Its stability below typical cooking and processing temperatures enables its use in heat-processed foods, improving product quality, reducing energy consumption, and allowing consistent rheological performance in baked, canned, and other processed food formulations.

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Author contributions N.V.N. Writing – original draft, Methodology, Formal analysis; F.T.T. Writing – review & editing, Validation; Project administration, Supervision, Validation.

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Data availability Data will be made available upon request from the corresponding author.

Declarations

Ethical approval Ethical approval for this study was granted by the Ethics Committee of the College of Agriculture and Environmental Sciences, University of South Africa (Approval No. 2022/CAES_HREC/079).

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors declare that they have no conflicts of interest.

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