

Sonicated Mucilage from Defatted Flaxseed Meal as a Sustainable Natural Gum: Functional and Thermal Characterization

Yağı Alınmış Keten Tohumu Küspesinden Sürdürülebilir Doğal Bir Gam Olarak Sonike Edilmiş Müsilaj: Fonksiyonel ve Termal Karakterizasyon

Elif YAVER^{1*}, Asuman KAN², Yüksel KAN³

Abstract

Flaxseed mucilage mainly consists of soluble fibers in the outermost layers of the seed. Because of its unique functional properties, such as water holding capacity, water absorption capacity, oil holding capacity and emulsion activity, it can be used as a natural gum in the food industry. Flaxseed mucilage can also exhibit certain health benefits, including anti-obesity, anti-diabetes, anti-cholesterol and antioxidant activities. In the current study, flaxseed mucilage was extracted from meal, which is a cold-pressed flaxseed oil by-product, by two different extraction methods: conventional extraction (3 h stirring at 50°C) and ultrasound-assisted extraction. The influences of ultrasound-assisted extraction at different durations (10, 20 and 30 min) on the yield, color, functional and thermal properties of flaxseed mucilage were compared with the conventional method. The maximum mucilage yield (17.46%) was obtained with ultrasound-assisted extraction for 30 min. Compared to the conventional method, ultrasound-assisted extraction elicited higher L^* and whiteness index values in mucilage samples. Moreover, flaxseed mucilage extracted by ultrasound-assisted extraction for 30 min had greater water holding capacity, water absorption capacity and solubility than the other mucilage samples. Besides that, the water and oil absorption capacities of flaxseed mucilage extracted by ultrasound-assisted extraction for 30 min were comparable to xanthan gum, and its solubility was higher. Gelatinization enthalpy (ΔH) values of mucilage samples extracted by conventional and ultrasound-assisted extraction methods were similar ($p>0.05$). The findings elucidated that flaxseed mucilage extracted from flaxseed meal by ultrasound-assisted extraction (30 min) is a natural, non-toxic and sustainable option for commercial gums, with high yield and good functional properties.

Keywords: Flaxseed mucilage, Ultrasound-assisted extraction, Oilseed meals, Functional properties, DSC

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Öz

Keten tohumu müsilağı, esas olarak tohumun en dış katmanlarında bulunan çözünür diyet liflerden oluşmaktadır. Su tutma kapasitesi, su absorpsiyon kapasitesi, yağ tutma kapasitesi ve emülsiyon aktivitesi gibi eşsiz fonksiyonel özellikleri sebebiyle, gıda endüstrisinde doğal bir gam olarak kullanılabilir. Keten tohumu müsilağı aynı zamanda; anti-obezite, anti-diyabet, anti-kolesterol ve antioksidan aktivite de dahil olmak üzere sağlık üzerine olumlu etkiler gösterebilmektedir. Bu çalışmada, konvansiyonel yöntem (50°C'de 3 saat çalkalama) ve ultrason destekli ekstraksiyon olmak üzere iki farklı ekstraksiyon yöntemi kullanılarak, soğuk sıkım keten tohumu yağı yan ürünü olan küspeden keten tohumu müsilağı ekstrakte edilmiştir. Farklı sürelerde (10, 20 ve 30 dk) uygulanan ultrason destekli ekstraksiyon yönteminin keten tohumu müsilağının verim, renk, fonksiyonel ve termal özellikleri üzerindeki etkileri, konvansiyonel yöntemle karşılaştırılmıştır. En yüksek müsilağ verimi (%17.46), 30 dk ultrason destekli ekstraksiyon yöntemi uygulaması ile elde edilmiştir. Konvansiyonel yöntemle karşılaştırıldığında, ultrason destekli ekstraksiyon yöntemi müsilağ örneklerinde daha yüksek L^* ve beyazlık indeksi değerleri sağlamıştır. Ayrıca; 30 dk ultrason destekli ekstraksiyon yöntemi uygulanarak ekstrakte edilen keten tohumu müsilağı, diğer müsilağ örneklerinden daha yüksek su tutma kapasitesi, su absorpsiyon kapasitesi ve çözünürlüğe sahipti. Bunun yanı sıra, 30 dk ultrason destekli ekstraksiyon yöntemi uygulanarak ekstrakte edilen keten tohumu müsilağı ksantan gımla karşılaştırılabilir su ve yağ absorpsiyon kapasitelerine sahipti ve çözünürlüğü daha yüksekti. Konvansiyonel yöntem ve ultrason destekli ekstraksiyon yöntemiyle ekstrakte edilen müsilağ örneklerinin jelatinizasyon entalpisi (ΔH) değerleri benzerdi ($p>0.05$). Bulgular, ultrason destekli ekstraksiyon yöntemiyle (30 dk) keten tohumu küspesinden yüksek verim ve iyi fonksiyonel özelliklerle ekstrakte edilen keten tohumu müsilağının, ticari gımlara karşı doğal, toksik olmayan ve sürdürülebilir bir seçenek olduğunu ortaya koymuştur.

Anahtar Kelimeler: Keten tohumu müsilağı, Ultrason destekli ekstraksiyon, Yağlı tohum küspesi, Fonksiyonel özellikler, DSC

1. Introduction

Seed mucilages are secreted from the seed coat epidermis to protect the organs against dehydration (Viudes et al., 2020). They can also play substantial roles in seed dispersal, germination, and abiotic stress tolerance and protect seeds from the digestion of animals (Galloway et al., 2020). Mucilages are composed of pectin, galacturonans, xylans, mannans, glucans and cellulose, responsible for their hydrophilicity (Phan and Burton, 2018). In the food industry, mucilages have been used as emulsifiers, thickeners, stabilizers, texturing agents and fat replacers (Safdar et al., 2020). Furthermore, their consumption could reduce the risks of several common diseases such as obesity, diabetes, cardiovascular diseases and some cancer types (Liu et al., 2021).

Flaxseed (*Linum usitatissimum*), a commercially important oil crop, is also a great source of dietary fibers, proteins, unsaturated fatty acids, lignans and bioactive compounds (Amiri et al., 2021; Karaca et al., 2025). Soluble dietary fibers in flaxseed are called mucilage, which is composed of acidic (pectin-like, 25%) and neutral (arabinoxylans, 75%) polysaccharides. Flaxseed mucilage also contains 4-20% proteins and 3-9% ash (Kaushik et al., 2017; Lorenc et al., 2022). It exhibits good functional and rheological properties attributed to its polysaccharide composition (Lorenc et al., 2022).

The extraction of flaxseed mucilage is conventionally carried out with hot water. However, hot water extraction takes a long time and reduces the purity of the mucilage. To enhance the yield and purity of the mucilage and decrease the extraction time, several researchers have developed novel extraction methods using alkali-acid, microwave (Safdar et al., 2020) and ultrasound (Fabre et al., 2015; Akhtar et al., 2019; Emadzadeh et al., 2022). Ultrasound-assisted extraction (UAE) is a popular technique for the extraction of mucilage from different seeds such as chia (Silva et al., 2022) and psyllium (Souza et al., 2020) since it is cost-effective, simple and environment-friendly. The researchers reported that the highest yield (Fabre et al., 2015) and purity (Safdar et al., 2020) in the extraction of flaxseed mucilage were obtained by UAE.

Flaxseed meal is produced as a by-product during oil extraction. Although high nutritional quality of flaxseed meal, it is widely used as animal feed. Puligundla and Lim (2022) stated that flaxseed meal is a commercially feasible source of extraction of mucilage. In most of the studies on the extraction of flaxseed mucilage, mucilage was extracted from whole/ground seeds or seed hull (Wang et al., 2010; Kaewmanee et al., 2014; Rocha et al., 2021; Emadzadeh et al., 2022; Yu et al., 2022). There are limited reports available in the literature on mucilage extraction from flaxseed meal (Fedeniuk and Biliaderis, 1994; Akhtar et al., 2019; Drozłowska et al., 2020). Fedeniuk and Biliaderis (1994) used the hot water extraction method for mucilage extraction from flaxseed meal and examined the chemical properties and viscosity of mucilage. In the study of Akhtar et al. (2019), flaxseed mucilage was extracted from the laboratory-defatted meal by UAE and the effects of temperature, pH, amplitude level and duration of sonication and water to meal ratio on the yield of flaxseed mucilage were examined. Drozłowska et al. (2020) extracted mucilage from flaxseed meal by hot water extraction and investigated its emulsifier properties.

To the best of our knowledge, this is the first report on the extraction of flaxseed mucilage from commercially cold-pressed flaxseed oil by-product (meal) by UAE using sonication bath and comparison of color and thermal properties of flaxseed mucilage extracted by the conventional method and UAE. Therefore, the study aimed to develop an alternative method by UAE at different durations (10, 20 and 30 min) to the conventional extraction method (3 h stirring at 50°C), and to compare yield, color, functional and thermal properties of flaxseed mucilages extracted by conventional and UAE methods.

2. Materials and Methods

2.1. Materials

Cold-pressed brown flaxseed (*Linum usitatissimum*) meal was supplied from Soivera (Tokat, Türkiye). Xanthan gum was purchased from Smart Kimya (İzmir, Türkiye).

2.2. Mucilage extraction

Conventional mucilage extraction was carried out by stirring flaxseed meal:distilled water mixture (1:20, w/v) at 50°C for 3 h (Yu et al., 2022).

UAE was performed at 50°C for three different durations (10, 20 and 30 min) using an ultrasonic bath (frequency: 35 kHz, power: 120 W; Bandelin, Sonorex RK 102 H, Berlin, Germany). Flaxseed meal was sonicated by mixing it with a ratio of 1:20 (w/v) distilled water.

After both extraction processes, the suspensions were filtered and the filtrates were centrifuged (Nüve NF800, Ankara, Türkiye) at 4300 rpm for 15 min. The supernatant was mixed with one volume of ethanol and then held at 4°C for 1 h to precipitate mucilage. The precipitated mucilage was collected by centrifugation at 4300 rpm for 10 min. Following this, the residue was dried in a hot-air oven (Nüve KD200) to 10% moisture content at 45°C and ground (Fakir Aromatic, Vaihingen, Germany) into powder (<250 µm).

2.3. Yield

The mucilage yield was computed using the following equation (Yu et al., 2022):

$$\text{Yield (\%)} = (\text{Weight of mucilage powder} / \text{Weight of flaxseed meal}) \times 100 \quad (\text{Eq. 1})$$

2.4. Color

Color L^* [lightness (100) to darkness (0)], a^* [redness (+) to greenness (-)] and b^* [yellowness (+) to blueness (-)] values of mucilage samples were measured by Minolta CR400 (Konica, Osaka, Japan). Chroma (C^*) and hue angle values were calculated by $(a^{*2} + b^{*2})^{1/2}$ and $\arctan(b^*/a^*)$, respectively. The whiteness index value was calculated using the following equation:

$$\text{Whiteness index} = 100 - [(100 - L^*)^2 + (a^*)^2 + (b^*)^2]^{1/2} \quad (\text{Eq. 2})$$

2.5. Functional analysis

2.5.1. Water holding capacity

One gram of sample (flaxseed mucilage/xanthan gum) was vortexed with 20 mL of distilled water for one minute. After 30 min, samples were subjected to centrifugation at 5000xg for 30 min. Following the removal of the supernatant, the precipitate was weighed. The amount of water retained by one gram of sample is expressed as water holding capacity (Kaushik et al., 2017) (Eq. 3).

$$\text{Water holding capacity (g g}^{-1}\text{)} = \text{Weight of precipitate} / \text{Weight of sample} \quad (\text{Eq. 3})$$

2.5.2. Water absorption capacity

The water absorption capacity of samples was determined according to the AACC 88-04 method (AACC, 2010) (Eq. 4).

$$\text{Water absorption capacity (g g}^{-1}\text{)} = \text{Weight of precipitate} / \text{Weight of sample} \quad (\text{Eq. 4})$$

2.5.3. Oil absorption capacity

The sample (0.5 g) was vortexed with 5 mL of sunflower oil for one minute. After 30 min, the mixture was centrifuged at 5000xg for 30 min. The supernatant was discarded, and the precipitate was weighed. The amount of oil retained by one gram of sample is expressed as oil absorption capacity (Kaushik et al., 2017) (Eq. 5).

$$\text{Oil absorption capacity (g g}^{-1}\text{)} = \text{Weight of precipitate} / \text{Weight of sample} \quad (\text{Eq. 5})$$

2.5.4. Solubility and swelling power

The suspension (250 mg sample:20 mL distilled water, w/v) was shaken in a water bath (Nüve ST30, Ankara, Türkiye) for 10 min at room temperature (25±2°C). After that, it was centrifuged at 3000 rpm for 15 min. The precipitate was weighed, and the supernatant was subjected to a drying process at 105°C until reaching a constant weight. Solubility and swelling power were computed using the following equations (Kaewmanee et al., 2014):

$$\text{Solubility (g 100 g}^{-1}\text{ sample)} = (\text{Weight of dried supernatant} / \text{Weight of sample}) \times 100 \quad (\text{Eq. 6})$$

$$\text{Swelling power (g g}^{-1}\text{ sample)} = \text{Weight of precipitate} / (\text{Weight of sample} - \text{Weight of dried supernatant}) \quad (\text{Eq. 7})$$

2.5.5. Emulsion capacity and emulsion stability

For the determination of emulsion capacity, 60 mL of the sample solution (0.5%) was homogenized with 6 mL of sunflower oil. Following this, the suspension was subjected to centrifugation at 4000 rpm for 10 min. The emulsion capacity was calculated using the following equation (Bazezew et al., 2022):

$$\text{Emulsion capacity (\%)} = (\text{Emulsified layer volume} / \text{Total volume}) \times 100 \quad (\text{Eq. 8})$$

For the determination of emulsion stability, the emulsion prepared as described above was heated at 80°C for 30 min. After cooling to room temperature, the emulsion was centrifuged (4000 rpm, 10 min). The emulsion stability was computed using the following equation (Bazezew et al., 2022):

$$\text{Emulsion stability (\%)} = (\text{Emulsified layer volume} / \text{Total volume}) \times 100 \quad (\text{Eq. 9})$$

2.6. Thermal analysis

Thermal analysis of flaxseed mucilage samples was made according to the method described by Rashid et al. (2019) using TA DSC25 (Delaware, USA). The sample (4 mg) was weighed in an aluminum pan and sealed. It was heated from 20 to 400°C at a heating rate of 10°C min⁻¹.

2.7. Statistical analysis

The calculations were made using three independent determinations for each of the previously noted variables. The results were analyzed by SPSS version 28.0 (IBM, Chicago, IL, USA) and presented as mean±standard deviation. One-way ANOVA was used to analyze of data. The significant differences between data means were determined using Duncan's mean comparison test at a 95% confidence level (p<0.05).

3. Results and Discussion

3.1. Extraction yield of mucilage samples

The extraction yield percentages are presented in *Table 1*. The yield of flaxseed mucilages changed between 11.66% and 17.46%. The yield of mucilage extracted from flaxseed meal by conventional method was 16.66%, values greater than reported in the literature for flaxseed mucilage extracted from whole/ground flaxseed [3.65% (Kaewmanee et al., 2014), 3.7% (Kaushik et al., 2017), 6.5% (Fabre et al., 2015), 8.92% (Safdar et al., 2020)]. The finding revealed that cold-pressed flaxseed meal cake is a feasible source to produce mucilage as a natural hydrocolloid. The yield of mucilage extracted by the conventional method was higher than mucilages extracted by UAE for 10 and 20 min (*Table 1*). However, the highest mucilage yield (17.46%) was obtained with UAE for 30 min. The result may be attributed to the cavitation effect of ultrasound. The cavitation can form microchannels on solid surfaces, thereby enhancing the diffusion of solvent into the cell and the speed of extraction (Wianowska and Gil, 2019). A study made by Fabre et al. (2015) stated that ultrasound (500 W, 22 kHz; 20, 40, 60, 80 and 100% amplitude with a 13 mm diameter probe) is a more efficient method in flaxseed mucilage extraction than the conventional magnetic stirring method. On the other hand, the mucilage yield was gradually increased with increasing sonication time (*Table 1*). Wang et al. (2022) suggested that acoustic cavitation would produce stronger shearing forces with longer sonication time, which could enhance the interaction between sample and solvent and lead to more mucilage layer leakage. The same trend was obtained by Safdar et al. (2020) for mucilage extracted from flaxseed by UAE (500 W, 22 kHz, 50% amplitude with 13 mm diameter probe).

Table 1. Yield values of flaxseed mucilage samples extracted by different methods

Extraction method	Yield (%)
Conventional	16.66±0.17 ^b
UAE-10	11.66±0.16 ^d
UAE-20	15.04±0.14 ^c
UAE-30	17.46±0.17 ^a

*Numbers in a column with different superscripts are significantly (p<0.05) different. UAE-10: Ultrasound-assisted extraction for 10 min. UAE-20: Ultrasound-assisted extraction for 20 min. UAE-30: Ultrasound-assisted extraction for 30 min.

3.2. Color values of mucilage samples

Color L^* , a^* , b^* , C^* , *hue* and whiteness index values of mucilages are shown in *Table 2*. Compared to UAE, the conventional extraction method resulted in lower L^* and whiteness index values in flaxseed mucilage. The decrease in L^* and whiteness index values may be due to the longer extraction time in the conventional method, therefore, damaging the seed coat parts and the leaching of impurities from flaxseed meal to hydrocolloid solution (Hedayati et al., 2021). On the other hand, L^* and whiteness index values of flaxseed mucilage extracted by UAE for 30 min were lower than mucilages extracted by UAE for 10 and 20 min (*Table 2*). Campos et al. (2016) reported that longer extraction duration promoted the transfer of pigments from the seed to soaking water. The brown-colored pigments may be responsible for the lower L^* and whiteness index values of mucilage extracted by UAE for 30 min (*Table 2*). The a^* values of mucilages have varied in the range of 0.86 to 1.49. The extraction method type did not show a remarkable change in a^* values of mucilages. The b^* , C^* and *hue* values of mucilage extracted by the conventional method and UAE for 30 min were similar and higher than samples extracted by UAE for 10 and 20 min. The results could be attributed to the longer extraction time in the conventional method and UAE for 30 min, which leaked more pigments and soluble solids from flaxseed meal to aqueous media (Campos et al., 2016; Hedayati et al., 2021). A similar decreasing trend in L^* values and an increasing trend in b^* values of sonicated mucilage with the increasing extraction time from 30 to 60 min were observed by Wang et al. (2022).

Table 2. Color values of flaxseed mucilage samples extracted by different methods

Extraction method	L^*	a^*	b^*	C^*	<i>Hue</i>	Whiteness index
Conventional	64.13±0.36 ^c	0.86±0.41 ^a	17.67±0.40 ^a	17.69±0.44 ^a	87.21±0.34 ^a	60.00±0.41 ^c
UAE-10	77.28±0.40 ^a	1.42±0.45 ^a	14.24±0.37 ^b	14.31±0.41 ^b	84.30±0.40 ^b	73.15±0.37 ^a
UAE-20	76.58±0.42 ^a	1.49±0.34 ^a	15.34±0.36 ^b	15.42±0.33 ^b	84.45±0.35 ^b	71.96±0.34 ^a
UAE-30	71.72±0.34 ^b	1.11±0.37 ^a	18.16±0.42 ^a	18.20±0.38 ^a	86.50±0.42 ^a	66.37±0.38 ^b

*Numbers in a column with different superscripts are significantly ($p < 0.05$) different. UAE-10: Ultrasound-assisted extraction for 10 min. UAE-20: Ultrasound-assisted extraction for 20 min. UAE-30: Ultrasound-assisted extraction for 30 min.

3.3. Functional properties of mucilage samples

In the current study, the functional properties of flaxseed mucilages extracted by the conventional method and UAE were presented by comparison with xanthan gum as a widely used commercial hydrocolloid in the food industry.

3.3.1. Water holding capacity

The greatest quantity of water that a hydrated sample can absorb and hold onto when subjected to an external force is known as its water holding capacity (Wang et al., 2022). Water holding capacities of flaxseed mucilages and xanthan gum are shown in *Figure 1*. Flaxseed mucilage extracted by the conventional method had a similar water holding capacity to mucilage extracted by UAE for 10 min. Furthermore, increasing the extraction time increased water holding capacity of flaxseed mucilage. The decrease in dehydration since sonication can be responsible for improving water holding capacity of flaxseed mucilage (Li et al., 2015). Besides that, Mir et al. (2019) suggested that the decrease in particle size and increase in solubility may be responsible for the increase in water holding capacity of flaxseed mucilage due to UAE. Amiri et al. (2018) obtained similar results on water holding capacity of myofibrillar proteins after 30 min sonication. However, water holding capacity values of flaxseed mucilages were lower than xanthan gum (*Figure 1*).

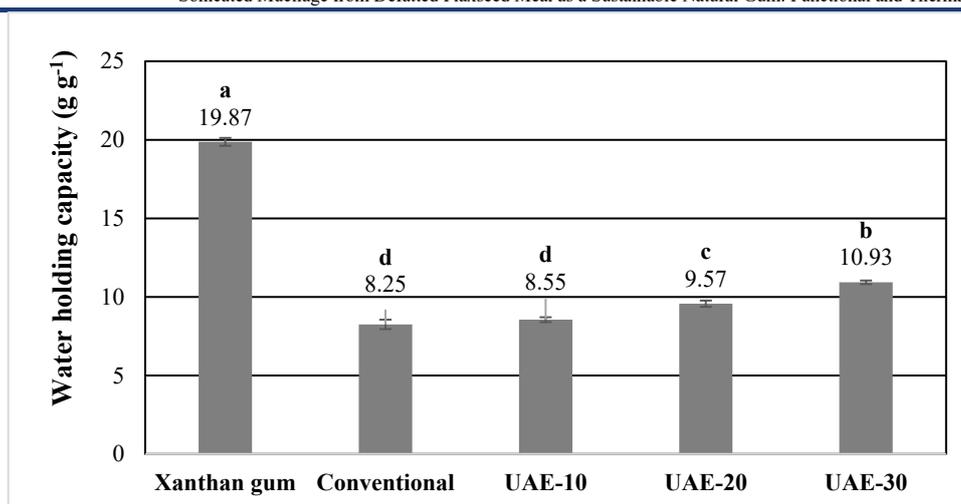


Figure 1. Water holding capacity of xanthan gum and flaxseed mucilage samples extracted by different methods

3.3.2. Water absorption capacity

The water quantity absorbed by a sample in excess water media is defined as its water absorption capacity. As shown in *Figure 2*, flaxseed mucilage extracted by UAE for 30 min had a comparable water absorption capacity to xanthan gum. Also, they showed the highest water absorption capacities. The increase in water absorption could be associated with hydrophilic components in foods such as polysaccharides and polar amino acid residues (Sreerama et al., 2012). Ultrasound treatment can break inter- and intra-molecular bonds, resulting in increased release of hydrophilic groups (Wang et al., 2017). The increase in the water absorption capacity of flaxseed mucilage could be attributed to the release of more hydrophilic groups and improved solubility after UAE. Amiri et al. (2018) also observed an increase in the water absorption capacity of myofibrillar proteins with increased sonication time. The authors concluded that the increase in water absorption capacity may be attributed to an increase in the protein surface area after ultrasound treatment due to a reduction in the particle size of proteins. Besides that, the water absorption capacity of flaxseed mucilage extracted by the conventional method was similar to mucilage extracted by UAE for 10 and 20 min (*Figure 2*).

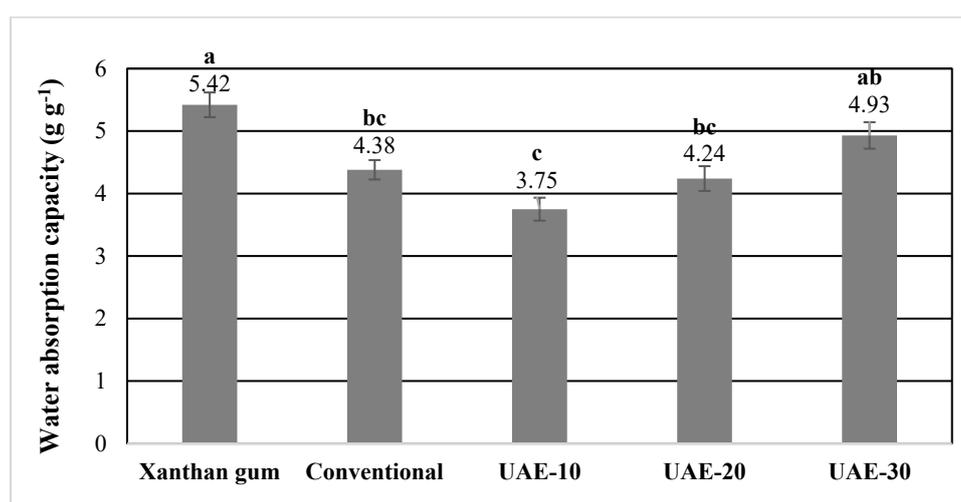


Figure 2. Water absorption capacity of xanthan gum and flaxseed mucilage samples extracted by different methods

3.3.3. Oil absorption capacity

In food technology, oil absorption capacity plays a crucial role in various foods, especially frozen pre-cooked products and biscuits, and improves flavor and textural properties of products (Tellez-Morales et al., 2020). The oil absorption capacity of flaxseed mucilage samples did not vary with the extraction method (*Figure 3*). All

samples elicited similar oil absorption capacities to each other. Besides, there was no significant ($p>0.05$) difference between the oil absorption capacities of flaxseed mucilages and xanthan gum. Wang et al. (2022) studied the effect of sonication time on the functional properties of chia seed mucilage. They reported that there is no change in the oil absorption capacity of chia mucilage with increasing ultrasound time. The oil absorption capacity of gums is vital in meat products, bakery products and ice cream (Rashid et al., 2019; Yilmaz et al., 2023). This finding showed that flaxseed mucilage is a good candidate for commercial usage as a fat substitute instead of xanthan gum.

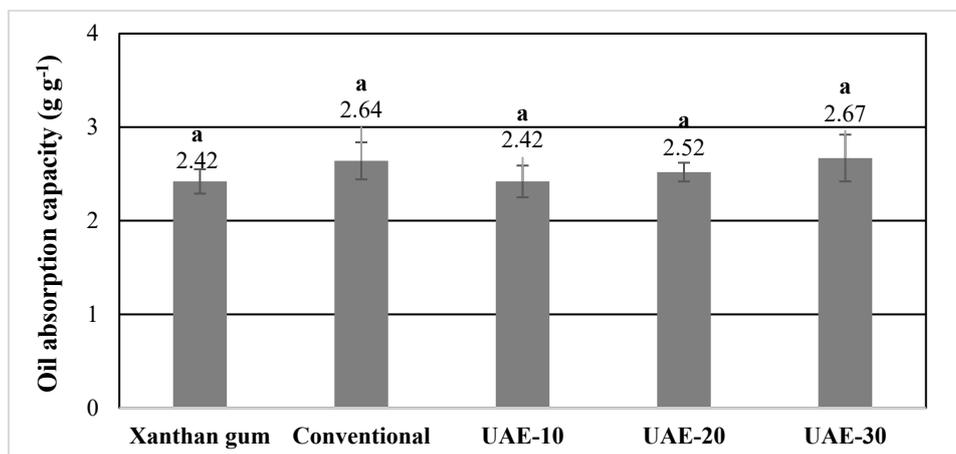


Figure 3. Oil absorption capacity of xanthan gum and flaxseed mucilage samples extracted by different methods

3.3.4. Solubility and swelling power

Figure 4 shows that UAE elicited a considerable improvement in the solubility of flaxseed mucilage compared to the conventional method. The solubility of flaxseed mucilages extracted by UAE was higher than sample extracted by the conventional method. Moreover, an increase in UAE duration gradually increased the solubility of flaxseed mucilage. The increase in solubility of flaxseed mucilage by UAE may be attributed to conformational changes in mucilage proteins and polysaccharides by cavitation. After sonication, hydrogen and hydrophobic bonds can break, which decreases the molecular weight of proteins/polysaccharides and increases protein/polysaccharide-water interactions (Jambrak et al., 2008; Wang et al., 2017; Nazari et al., 2018). Emadzadeh et al. (2022) compared the solubility of ultrasound-extracted (700 W, 24 kHz, 20 min) flaxseed gum with the conventionally extracted sample. They found that the solubility of ultrasound-extracted gum was greater than conventionally extracted gum. On the other hand, flaxseed mucilages exhibited notably higher solubility than xanthan gum (Figure 4). The high solubility of flaxseed mucilage extracted by UAE indicated the potential for industrial application as a hydrocolloid (Souza et al., 2020).

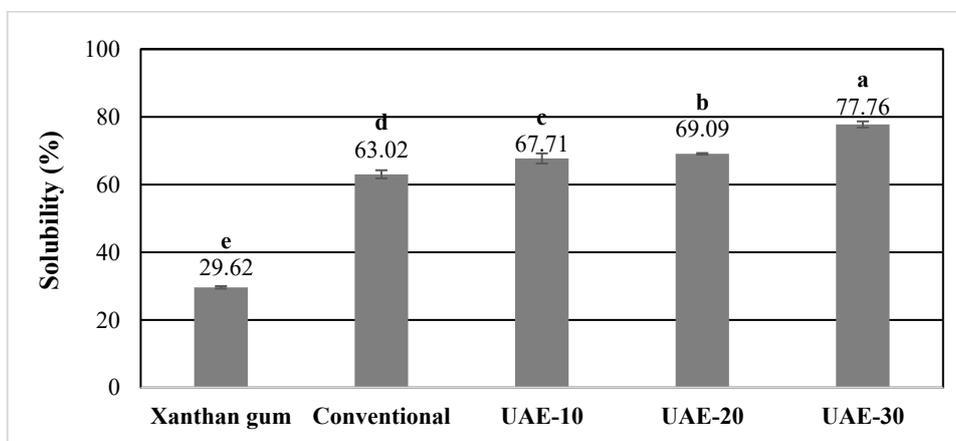


Figure 4. Solubility of xanthan gum and flaxseed mucilage samples extracted by different methods

Similar to the solubility, flaxseed mucilages extracted by UAE had greater swelling power values than conventionally extracted mucilage (Figure 5). Among the mucilages, the highest swelling power was observed in flaxseed mucilage extracted by UAE for 10 min. The increase in swelling power in mucilages by UAE could be related to increasing the amount of hydroxyl groups in polysaccharides after sonication. As a result of the breakage of inter- and intra-bonds in cell wall polysaccharides by sonication, the amount of hydroxyl groups increases, and swelling power improves (Gharibzahedi et al., 2018). Manchun et al. (2012) also found an increase in the swelling power and solubility of tapioca starch after sonication. Besides that, the swelling power of flaxseed mucilages was lower than xanthan gum (Figure 5).

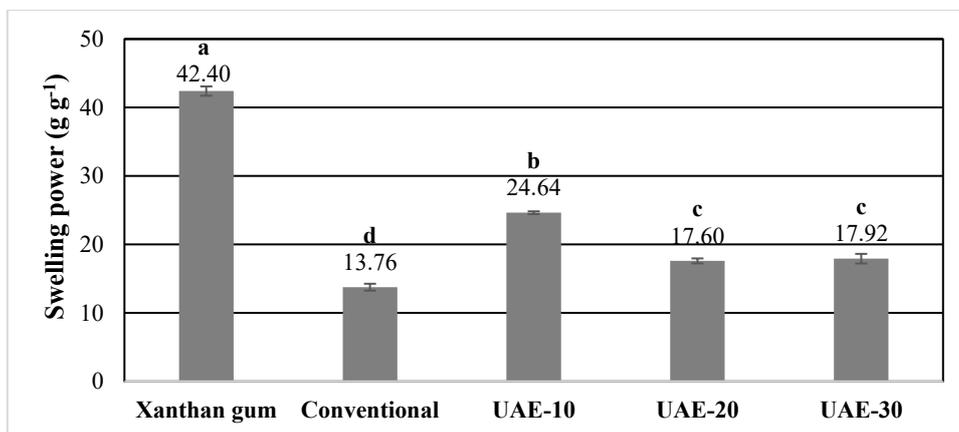


Figure 5. Swelling power of xanthan gum and flaxseed mucilage samples extracted by different methods

3.3.5. Emulsion capacity and emulsion stability

The emulsification capabilities of polysaccharides depend on their compositions, molecular weights, surface charges and hydrophobic components (Pereira et al., 2019). The emulsion capacity and emulsion stability of flaxseed mucilages were found to be slightly lower than xanthan gum (Figure 6). The extraction type had no negative impact on the emulsion capacity and emulsion stability of flaxseed mucilages. Akl et al. (2021) also observed that the emulsion properties of garden cress seed mucilage extracted by UAE were similar to conventionally extracted mucilage.

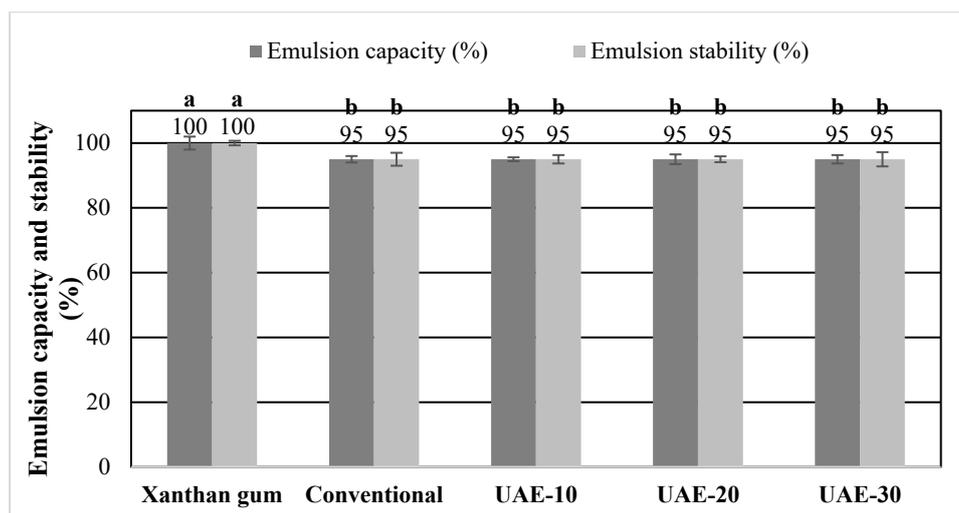


Figure 6. Emulsion capacity and emulsion stability of xanthan gum and flaxseed mucilage samples extracted by different

3.4. DSC measurements of mucilage samples

DSC measurements are often performed to investigate the thermal behavior of biopolymers, especially polysaccharides (Rashid et al., 2019). DSC analysis results of flaxseed mucilages extracted by conventional and UAE methods are demonstrated in Table 3. The endothermic peak at ~60°C is associated with the quantity of

energy used to release water from the mucilages (Morales-Chavez et al., 2024). Gelatinization onset temperatures (T_{Onset}), peak temperatures (T_{Peak}) and endset temperatures (T_{Endset}) of flaxseed mucilages varied between 49.69-53.36°C, 41.93-89.82°C and 44.29-61.19°C, respectively. T_{Onset} and T_{Peak} values of flaxseed mucilage extracted by 30 min were lower than mucilage extracted by the conventional method. The results may be due to the conformational changes in mucilage after ultrasonic treatment (Nazari et al., 2018). Thermal behavior of mucilages is notably affected by chemical conformation, molecular weight, functional groups and branched chains of polysaccharides (Madera-Santana et al., 2006). On the other hand, T_{Endset} value of flaxseed mucilage extracted by UAE for 30 min was close to that of its conventionally extracted counterpart (Table 3).

Table 3. DSC measurements of flaxseed mucilage samples extracted by different methods

Extraction method	T_{Onset} (°C)	T_{Peak} (°C)	T_{Endset} (°C)	ΔH (J g ⁻¹)
Conventional	51.97±0.51 ^{ab}	51.97±0.52 ^c	61.19±0.55 ^a	0.83±0.58 ^a
UAE-10	53.36±0.45 ^a	62.97±0.55 ^b	58.61±0.61 ^b	0.96±0.51 ^a
UAE-20	49.69±0.58 ^c	89.82±0.47 ^a	44.29±0.47 ^c	0.91±0.47 ^a
UAE-30	50.71±0.52 ^{bc}	41.93±0.57 ^d	60.67±0.59 ^{ab}	1.09±0.46 ^a

*Numbers in a column with different superscripts are significantly ($p < 0.05$) different. T_{Onset} : Gelatinization onset temperature. T_{Peak} : Gelatinization peak temperature. T_{Endset} : Gelatinization endset temperature. ΔH : Gelatinization enthalpy. UAE-10: Ultrasound-assisted extraction for 10 min. UAE-20: Ultrasound-assisted extraction for 20 min. UAE-30: Ultrasound-assisted extraction for 30 min.

The enthalpy (ΔH) of flaxseed mucilages extracted by conventional method and UAE has varied in the range of 0.83 to 1.09 J g⁻¹ (Table 3). Variations in the ΔH values between conventionally and ultrasonically extracted flaxseed mucilages were not statistically significant ($p > 0.05$).

4. Conclusions

This study was undertaken to characterize yield, color, functional and thermal characteristics of flaxseed mucilages extracted from cold-pressed flaxseed oil meal by conventional and UAE (for 10, 20 and 30 min) methods and to see the potential of flaxseed mucilage as a natural gum to commercial counterparts. According to data, UAE for 30 min elicited maximum mucilage yield and a higher whiteness index than conventionally extracted mucilage. Functional properties (especially water holding capacity, water absorption capacity, solubility and swelling power) of flaxseed mucilage were considerably enhanced with UAE for 30 min. The findings demonstrated that flaxseed mucilage exhibited comparable water absorption capacity, oil absorption capacity and emulsifying properties (both showed emulsifying capabilities >90%) and greater solubility compared to commercial gum. Extraction methods did not change the ΔH values of flaxseed mucilages. As a result, UAE (especially for 30 min) can be used as green extraction technology to improve functional attributes of gums and make modified mucilages as potential ingredients in various food productions, including bakery goods, dairy products and confectionery.

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Ethical Statement

There is no need to obtain permission from the ethics committee for this study.

Conflicts of Interest

We declare that there is no conflict of interest between us as the article authors.

Authorship Contribution Statement

Concept: Yaver, E.; Design: Yaver, E.; Data Collection or Processing: Yaver, E., Kan, A.; Statistical Analyses: Yaver, E.; Literature Search: Yaver, E., Kan, Y.; Writing, Review and Editing: Yaver, E.

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