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Research Article

IMPACT OF CHITOSAN-BASED GELLED EMULSION ON THE QUALITY CHARACTERISTICS OF REFORMULATED MEAT EMULSIONS

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ABSTRACT
This study investigated the effects of substituting beef fat with chitosan-based gelled emulsions (GEs), prepared using punicic acid-rich pomegranate seed oil (PSO), at various levels (50%, 75%, and 100%) on the quality characteristics of model meat emulsions. Utilizing GEs in an oil-in-water (O/W) emulsion form is a strategic approach intended to mimic the structural function of solid animal fat. Chemical analyses revealed that GE application resulted in the most favorable nutritional profile, particularly at the 50% replacement level (GE50), which recorded the highest moisture (64.96%) and protein (20.75%) content, along with the lowest fat content (11.85%) compared to the control group. Conversely, the 75% replacement group (GE75) unexpectedly exhibited the lowest moisture (59.49%) and the highest total fat content (16.29%). Furthermore, all GE applications significantly lowered the pH value of the emulsions compared to the control. Regarding techno-functional properties, the inclusion of GE led to an increase in Total Expressible Fluid (TEF). Crucially, the GE100 group (in which GE fully replaced fat) exhibited the lowest Total Expressible Fat (EFAT) value, indicating a high fat-holding capacity before cooking. However, all replacement levels significantly increased the Jelly and Fat Separation (JFS) ratio, negatively impacting the emulsion stability during storage. The cooking characteristics were partially inconsistent with the EFAT results; all GE groups experienced significant losses in moisture retention, fat retention, and cooking yield compared to the control. In this context, the GE75 group demonstrated the lowest cooking yield (63.05%), while the GE100 group exhibited the poorest fat retention performance (58.41%). This inconsistency suggests that the expected yield could not be achieved during the complex cooking process due to the shrinkage of the gel matrix and the loss of the gel-immobilized oil. Textural analyses indicated a decrease in hardness and gumminess values as the GE ratio increased, and microstructural evaluations confirmed that GE-containing formulations formed a more homogeneous and smoother matrix compared to the control. Consequently, while chitosan-based GEs offer potential for nutritional improvement, especially at the GE50 level, further optimization of the formulation and/or processing parameters is mandatory to enhance the emulsion stability during cooking and storage.

Keywords: Chitosan, gelled emulsion, pomegranate seed oil, meat emulsion, quality

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KİTOSAN BAZLI JEL EMÜLSİYONUN YENİDEN FORMÜLE EDİLMİŞ ET EMÜLSİYONLARININ KALİTE KARAKTERİSTİKLERİ ÜZERİNE ETKİSİ

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ÖZET

Bu çalışma, model et emülsiyonlarının kalite karakteristikleri üzerindeki etkilerini değerlendirmek amacıyla, sığır yağının yerine punikik asit açısından zengin nar çekirdeği yağı kullanılarak hazırlanan kitosan bazlı jel emülsiyonların (JE) farklı oranlarda (%50, %75 ve %100) ikamesini araştırmıştır. JE'nin O/W jel emülsiyon formunda kullanılması, hayvansal yağın yapısal işlevini taklit etmeyi amaçlayan bir stratejidir. Kimyasal analizler, JE uygulamasının, özellikle %50 ikame seviyesinde (GE50), kontrol grubuna göre en yüksek nem (%64,96) ve protein (%20,75) içeriği ile en düşük yağ içeriğini (%11,85) kaydederek en elverişli besin profilini sunduğunu göstermiştir. Buna karşın, %75 ikame grubu (GE75) beklenenin aksine en düşük nem (%59,49) ve en yüksek toplam yağ içeriğine (%16,29) sahip olmuştur. Ayrıca, tüm JE uygulamalarının emülsiyonların pH değerini kontrole göre anlamlı ölçüde düşürdüğü belirlenmiştir. Tekno-fonksiyonel özellikler incelendiğinde ise JE kullanımı ile Toplam Ayrılan Sıvı (TAF) değerlerinin artış gösterdiği gözlenirken yağın tamamen JE ile ikame edildiği GE100 grubunun en düşük Toplam Ayrılan Yağ (TAY) değerine sahip olduğu saptanmıştır. Bu noktadan yola çıkılarak %100 ikame edilen grubun yağ tutma kapasitesinin yüksek olduğu söylenebilir. Bununla birlikte, tüm ikame seviyeleri, Ayrılan Jel ve Yağ (AJY) oranını anlamlı ölçüde artırarak emülsiyon stabilitesini olumsuz etkilemiştir. Pişirme karakteristikleri, TAY sonuçlarıyla kısmen tutarsızlık göstermiş; tüm JE grupları kontrole kıyasla nem tutma, yağ tutma ve pişirme veriminde anlamlı kayıplar yaşamıştır. Bu bağlamda, GE75 grubu en düşük pişirme verimini (%63,05) gösterirken, GE100 grubu en düşük yağ tutma (%58,41) performansını sergilemiştir. Bu tutarsızlık, karmaşık pişirme sürecinde jel matrisinin küçülmesine ve jel içinde hapsedilmiş yağın kaybına yol açarak beklenen verimin sağlanamadığını düşündürmektedir. Tekstürel analizlerde, JE oranının artmasıyla sertlik ve sakızımsılık değerlerinde azalma gözlenmiştir; mikroyapısal incelemeler ise JE içeren formülasyonlarda kontrol grubuna kıyasla daha homojen ve pürüzsüz bir matris oluştuğunu teyit etmiştir. Sonuç olarak, kitosan bazlı jel emülsiyonlar özellikle GE50 seviyesinde besin profilini iyileştirme potansiyeli sunsa da emülsiyon stabilitesini artırmak için formülasyon ve/veya işlem parametrelerinde ek optimizasyonun zorunlu olduğu düşünülmektedir.

Keywords: Kitosan, jel emülsiyon, nar çekirdeği yağı, et emülsiyonu, kalite

INTRODUCTION

Beef fat is a key component in meat products due to its contributions to texture, juiciness, emulsion stability, and overall technological performance (Schumacher et al., 2022). However, the demand for healthier meat products has led to the use of vegetable oils (e.g., walnut, linseed, olive, rapeseed, pumpkin seed), marine oils (e.g., algal oil), and structured lipid systems (gelled emulsions, oleogels, hydrogels, and microencapsulated oils) as alternatives to animal fat (Lima et al., 2022). On the other hand, the direct incorporation of liquid vegetable oils into meat matrices often leads to challenges such as increased cooking loss, reduced emulsion stability, weakened texture, and overall deterioration of product quality, since liquid oils do not provide the structural functionality that solid animal fat naturally offers (Lima et al., 2022). Additionally, the tendency of liquid oils to easily migrate or be expelled during mixing, heating, or storage leads to poor fat retention and inconsistent product characteristics (Santhi et al., 2017). To overcome these limitations, structuring oils within gelled emulsions has emerged as an effective strategy. Gelled emulsions (GEs) entrap the oil phase within a stable three-dimensional network, enhancing its retention during processing and enabling it to mimic the physical role of animal fat better (Zhu et al., 2018; Su et al., 2024). In this way, they support desirable textural attributes and technological performance, making them a promising tool for developing reformulated meat products with maintained quality (Alejandre et al., 2016; Serdaroğlu et al., 2017; Pintado et al., 2018; Kavuşan et al., 2020; Botella-Martínez et al., 2021; Nacak et al., 2021; Paglarini et al., 2022; Lee et al., 2023; Serdaroğlu et al., 2024).

Chitosan has been extensively investigated as an oleogelator due to its unique properties—including biodegradability, biocompatibility, antimicrobial activity, and the ability to form robust networks (Brito et al., 2022; Lama et al., 2024; Miao et al., 2024). Furthermore, researchers have reported that chitosan-based oleogels are utilized as fat replacers in meat products, successfully reducing saturated fat content and improving nutritional profiles while maintaining desirable texture and sensory qualities (Çalişkan et al., 2024; Wang et al., 2024). Nonetheless, its application in a chitosan-based gelled emulsion formulation has not yet been reported.

Pomegranate seed oil (PSO) is a rich source of punicic acid, a valuable conjugated linolenic acid, alongside various other unsaturated fatty acids, phytosterols, and tocopherols. Its diverse composition provides it with notable antioxidant, antimicrobial, immunomodulatory, anticancer, and lipid metabolism-regulating properties (Boroushaki et al., 2016). Although PSO has been directly incorporated into sausage formulations previously (Hoseini et al., 2020), and a chitosan and pomegranate seed oil emulgel/oleogel formulation has been developed (for non-food applications like dermal delivery, for instance) (Bagińska et al., 2024), no research has yet demonstrated the use of this specific formulation in final food products, such as meat products. While efforts to replace beef fat in meat emulsions often compromise textural integrity and emulsion stability, the current literature lacks comprehensive studies on novel biopolymer-based structures. Therefore, this study uniquely utilizes chitosan-based GEs as a functional fat replacer to specifically investigate their impact on mitigating these technological challenges and enhancing the overall quality attributes (chemical, technological, and textural) of model meat emulsions.

MATERIALS and METHODS

Materials

Beef with a composition of 73.6% moisture, 20.7% protein, 4.2% fat, and 1.5% ash, together with beef fat containing 95.7% lipids, 4.2% moisture, and 0.1% ash, was obtained from a local butcher in Izmir for the preparation of model meat emulsions (MEs). For O/W gelled emulsion formulation, chitosan (80% degree of deacetylation) and pomegranate seed oil were sourced from Nurbal Şifa Aktar Natural Food Industry Trade (Istanbul, Turkey) and Smart Kimya Tic. ve Dan. (Izmir, Turkey), respectively. The fatty acid composition of the pomegranate seed oil consisted of palmitic acid (8.0%), stearic acid (3.87%), oleic acid (14.0%), linoleic acid (15.22%), and punicic acid (50.17%). Curing agents were procured from Fansada Aroma and Spice Food Products (Ankara, Turkey). All analytical-grade chemicals used in the study were supplied by Sigma-Aldrich Chemie GmbH (Schnelldorf, Germany).

Preparation of O/W gelled emulsion

The optimal phase ratios for producing an O/W gelled emulsion through heat-induced gelation were determined through preliminary trials, based on the methods described by Poyato et al. (2014) and Paradiso et al. (2015). In these trials, the gelled emulsion was composed of two primary phases: an oil phase (pomegranate seed oil) and an aqueous phase containing chitosan. The chitosan was incorporated at a concentration of 10% of the aqueous phase, which was found to provide a stable gel structure, as confirmed by preliminary tests on viscosity and texture. The microstructural characteristics of the gelled emulsion are shown in Figure 1. The liquid phase of the emulsion was prepared by adding chitosan to water and heating the mixture to 65°C. The pomegranate seed oil, which constituted the oil phase, was heated to 55°C. The water and oil phases were then emulsified using a Thermomix (Thermomix, Vorwerk, Germany) at 5800 rpm for 3 min. The resulting gel emulsions were allowed to set at +4°C for 24 h.

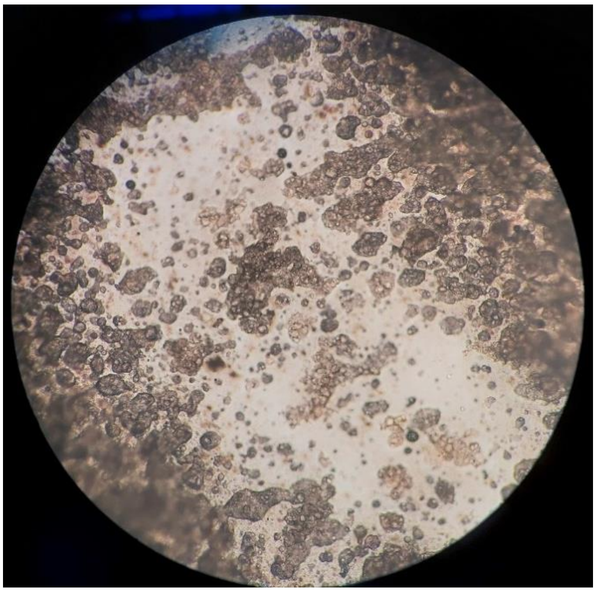

Figure 1. Microscope image (100×) of the O/W gelled emulsion.

Production of model meat emulsion and experimental design

The model meat emulsions (MEs) were prepared following the general approach of Zungur et al. (2015), with beef fat and/or gelled emulsion serving as the fat source. Four different formulations were designed: (1) an emulsion containing only beef fat (control, CNT), (2) a formulation in which 50% of the fat was replaced with gelled emulsion (GE50), (3) a formulation incorporating 75% gelled emulsion (GE75), and (4) an emulsion in which the entire fat content was substituted with gelled emulsion (GE100). All four treatments were produced in duplicate on two separate production days, as outlined in Table 1.

Table 1. Formulation of model meat emulsions

Treatments*	Ingredients (%)						
	Beef	Beef fat	GE	Ice	Salt	STTP	Sodium nitrite
CNT	68	20	-	10	2	0.5	0.015
GE50	68	10	10	10	2	0.5	0.015
GE75	68	5	15	10	2	0.5	0.015
GE100	68	-	20	10	2	0.5	0.015

*The treatments were formulated by: CNT: Standard-fat control (20% beef fat). GE50: 50% beef fat replacement with GE. GE75: 75% beef fat replacement with GE. GE100: 100% beef fat replacement with GE. STTP: Sodium Tripolyphosphate.

Initially, the beef and beef fat were processed using a 3-mm plate grinder (Arnica W2000 Grande, Istanbul, Turkey). The minced beef was then homogenized in a Thermomix (Thermomix, Vorwerk, Germany) at 39×g for 1 min. After this initial mixing, NaCl, STTP and sodium nitrite were incorporated, and the mixture was further homogenized for 2 min at the same speed. Subsequently, half of the ice and the designated fat source (beef fat and/or gelled emulsion) were added and mixed at 188×g for 3 min. The remaining ice was then introduced, and blending continued for an additional 3 min. Subsequently, the meat batter was emulsified at 622×g for 1 min. To remove entrapped air, the emulsions were transferred into 50-mL centrifuge tubes and centrifuged at 971×g for 1 min (Nüve NF 400). Following deaeration, the tubes were heated in a water bath (Nüve) at 70°C for 30 min. After the heating step, the samples were allowed to cool to room temperature before further analysis.

Chemical composition and pH

Moisture and ash levels were determined in accordance with AOAC (2012) procedures, while fat content was quantified using the method described by Flynn and Bramblet (1975). Protein concentration was measured via the Dumas combustion technique with a LECO Protein/Nitrogen Analyzer (FP-528; Leco, St. Joseph, MI, USA). The pH of the samples was evaluated following the procedure reported by Nacak et al. (2021).

Emulsion stability

Emulsion stability was evaluated using the procedure described by Hughes et al. (1997). The amounts of total expressible fluid (TEF) and expressible fat (EFAT) were quantified using the equations below:

$$TEF = (Weight\ of\ centrifuge\ tube + sample) - (Weight\ of\ centrifuge\ tube + pellet)$$

$$TEF\ (\%) = \frac{TEF}{Weight\ of\ sample} \times 100$$

$$EFAT\ (\%) = \frac{(Weight\ of\ crucible + dried\ supernatant) - (Weight\ of\ centrifuge\ tube + sample)}{TEF} \times 100$$

Jelly and fat separation

Jelly and fat separation (JFS) was assessed according to the approach of Bloukas and Honikel (1992). A 200 g portion of the emulsion was placed into glass jars, strained through a sieve, and heated in a boiling water bath (Nüve) until the internal temperature reached 90°C. After cooling to room temperature, samples were stored at 4°C for 24 h. The jars were subsequently reheated at 45°C for 1 h, and the released jelly and fat were collected in a graduated cylinder for volume measurement. JFS was then expressed as the proportion of separated jelly and fat relative to the initial batter weight.

Fat and moisture retention

Fat retention represents the proportion of fat remaining in the product after cooking. It was calculated using the following equation proposed by Murphy et al. (1975):

$$\text{Fat Retention (\%)} = \frac{(\text{cooked weight} \times \text{\%fat in cooked product})}{(\text{raw weight} \times \text{\%fat in raw product})} \times 100$$

Moisture retention indicates the amount of moisture retained in the cooked product per 100 g of sample. It was determined according to the formula reported by El-Magoli et al. (1996):

$$\text{Moisture Retention (\%)} = \frac{(\text{\%yield} \times \text{\%moisture in product})}{100}$$

Processing yield

To determine the processing yield of the model meat emulsion samples, the batters were first filled into tubes and weighed (W1). Following the heat treatment and centrifugation steps, the final weights of the samples were recorded again (W2). The processing yield was calculated using the following equation:

$$\text{Processing Yield (\%)} = \frac{W1 - W2}{W1} \times 100$$

Texture profile analysis

Texture profile measurements were performed using a TA-XT2 texture analyzer (Stable Micro Systems, Haslemere, UK). Hardness (N), springiness (mm), cohesiveness, gumminess (N), and chewiness (N×mm) were quantified. Cylindrical samples (2.5 cm height × 2.2 cm diameter) were compressed twice to 50% of their initial height. The test conditions included a crosshead speed of 1 mm/s, a post-test speed of 2 mm/s, and a test speed of 1 mm/s, with measurements taken using a 30-kg load cell.

Scanning electron microscopy (SEM)

The microstructural characteristics of the meat emulsions were examined using a scanning electron microscope (Thermo Scientific Apreo 2, Waltham, MA, USA). Before imaging, the samples were dried, ground into a fine powder, and mounted onto conductive stubs. A thin gold layer was then sputter-coated onto the surface using a QUORUM Q150 RES rotary pumped coater (East Sussex, UK) to ensure adequate conductivity. The coated samples were subsequently placed in the SEM chamber and evacuated to a pressure of 1×10^{-3} mBar. Once the desired vacuum and voltage conditions were reached, high-voltage imaging was initiated. The interaction of the electron beam with the sample surface produced the micrographs used for structural evaluation.

Statistical analysis

All statistical analyses were conducted using the General Linear Model (GLM) procedure in SPSS software (version 22.0; IBM, Armonk, NY, USA). The experiment consisted of four formulation groups (CNT, GE50, GE75, and GE100), which were treated as fixed effects. Each formulation was produced in two independent batches, and all quality measurements were performed in triplicate for each batch. To assess the effect of replacing beef fat with gelled emulsion on the quality attributes of the meat emulsions, a one-way analysis of variance (ANOVA) was employed. When significant differences were detected among treatments, mean comparisons were performed using Duncan's multiple range test at the 95% confidence level.

RESULTS AND DISCUSSION

Chemical composition and pH

The chemical composition and pH values of the model meat emulsions are presented in Table 2. The incorporation of GE as a fat replacer resulted in significant effects on the moisture, protein, fat, and ash content of the formulations ($p < 0.05$). The GE50 group (50% fat replacement) exhibited the highest moisture (64.96%) and protein (20.75%) content ($p < 0.05$), while simultaneously showing the lowest fat content (11.85%) ($p < 0.05$) compared to the control (CNT). Studies consistently report higher moisture in GE-containing samples, especially at moderate replacement levels (Serdaroğlu et al., 2016; Botella-Martínez et al., 2023; Lazăr et al., 2023). Conversely, the GE75 group (75% replacement) displayed the lowest moisture (59.49%) and ash (2.61%) content ($p < 0.05$) yet unexpectedly registered the highest total fat content (16.29%) ($p < 0.05$). The fully substituted GE100 group yielded results similar to those of the CNT group for both moisture (62.53%) and fat (12.62%) content ($p > 0.05$), however maintained a significantly higher protein content (18.48%) than the control ($p < 0.05$). Protein content often rises with GE addition, particularly when the gel matrix includes protein-rich ingredients (e.g., gelatin, whey protein, buckwheat flour). This effect is most pronounced at higher replacement levels or when protein-based gelling agents are used (Botella-Martínez et al., 2023; Lazăr et al., 2023; Idyryshev et al., 2025).

Additionally, all GE applications (GE50, GE75, and GE100) significantly lowered the pH value of the emulsions compared to the CNT group (6.29) ($p < 0.05$), suggesting an impact from the GE components on the overall acidity. All levels of GE incorporation tend to lower the pH of meat emulsions compared to controls, attributed to the slightly acidic nature of many GE components (e.g., plant proteins, inulin, and certain oils) (Serdaroğlu et al., 2016; Idyryshev et al., 2025). This pH drop can influence protein solubility and water-holding capacity, potentially improving emulsion stability and cooking yield.

Overall, the GE50 provided the most favorable nutritional profile. Conversely, the GE100 demonstrated success in fully replacing the fat content while ensuring that the total fat level remained comparable to the control group.

Table 2. Chemical composition and pH value of model meat emulsions

Treatments*	Moisture (%)	Fat (%)	Protein (%)	Ash (%)	pH
CNT	61.92±0.66[b]	12.48±1.48[b]	15.26±1.01[c]	2.81±0.06[a]	6.29±0.08[a]
GE50	64.96±0.23[a]	11.85±0.96[b]	20.75±0.28[a]	2.71±0.06[b]	6.20±0.01[b]
GE75	59.49±0.22[c]	16.29±0.09[a]	18.88±0.58[b]	2.61±0.01[c]	6.13±0.01[b]
GE100	62.53±0.45[b]	12.62±0.70[b]	18.48±0.84[b]	2.60±0.01[c]	6.15±0.01[b]

*The treatments were formulated by: CNT: Standard-fat control (20% beef fat). GE50: 50% beef fat replacement with GE. GE75: 75% beef fat replacement with GE. GE100: 100% beef fat replacement with GE. a–c Different letters in the same column indicate significant differences ($p<0.05$).

Techno-functional properties

The techno-functional properties of the model me2qwat emulsions, including Total Expressible Fluid (TEF), Total Expressible Fat (EFAT), and Jelly and Fat Separation (JFS), showed significant differences ($p < 0.05$) among the treatments (Table 3). All reformulated groups exhibited significantly higher TEF values compared to CNT (8.10%). Specifically, the GE75 recorded the highest TEF (34.46%) ($p < 0.05$). Conversely, the effect on EFAT varied: the GE100 group showed the lowest EFAT (10.95%) ($p < 0.05$), indicating superior fat retention during heating compared to the CNT (14.24%) and the GE50 group, which showed the highest EFAT (23.19%) ($p < 0.05$). Similar to our results, some researchers reported that fat exudation during heating is reduced with higher GE incorporation, especially at full replacement, indicating superior fat retention (Serdaroğlu et al., 2016; Serdaroğlu et al., 2024; Idyryshev et al., 2025).

Furthermore, all GE replacement levels (GE50, GE75, and GE100) resulted in significantly higher JFS values compared to the CNT (13.87%), with 29.85% in GE75 ($p < 0.05$). This phase separation is likely due to the gel matrix's inability to maintain integrity under heat treatment, leading to water and fat migration out of the emulsion (Lazăr et al., 2023). In line with our results, oleogel formulated with chitosan and pomegranate seed oil resulted in the highest JFS values in the groups where more than 50% (75% and 100% replacement) of the animal fat was replaced (Çalişkan et al., 2024).

Table 3. Techno-functional properties of model meat emulsions

Treatments*	TEF (%)	EFAT (%)	Jelly and Fat Separation (%)
CNT	8.10±0.68^{c}	14.24±1.07^{c}	13.87±0.87^{b}
GE50	28.91±1.14^{b}	23.19±0.91^{a}	28.14±1.69^{a}
GE75	34.46±0.58^{a}	21.33±0.58^{b}	29.85±0.09^{a}
GE100	27.47±1.24^{b}	10.95±0.20^{d}	28.30±1.45^{a}

*The treatments were formulated by: CNT: Standard-fat control (20% beef fat). GE50: 50% beef fat replacement with GE. GE75: 75% beef fat replacement with GE. GE100: 100% beef fat replacement with GE. a–d Different letters in the same column indicate significant differences ($p<0.05$).

Cooking characteristics

The cooking characteristics of the model meat emulsions were significantly affected by the GE replacement levels ($p < 0.05$), with the CNT consistently demonstrating superior performance in all three parameters ($p < 0.05$). The CNT group achieved the highest moisture retention (55.55%), fat retention (87.56%), and cooking yield (89.71%). Conversely, all GE-substituted groups showed a decrease in these properties. GE75 exhibited the lowest moisture retention (37.51%) and cooking yield (63.05%), indicating the highest overall cooking loss. The GE100 group recorded the lowest fat retention (58.41%), suggesting that the total replacement of beef fat severely compromises the emulsion's ability to retain fat during cooking. This decline in cooking properties appears partially inconsistent with the results from the techno-functional analysis (Table 3), where GE significantly increased TEF values ($p < 0.05$). Most research shows a decline in moisture retention and cooking yield as GE levels increase, with the lowest values typically observed at full (100%) replacement (Serdaroğlu et al., 2016; Wang et al., 2023). This is attributed to the dilution of meat proteins and the inability of some GE matrices to bind water as effectively as animal fat (Ren et al., 2022).

Although TEF values were high, implying better resistance to separation during heating, this stability did not translate into improved moisture or fat retention. However, the EFAT results show some correlation with cooking yield: the GE100 group, which had the lowest EFAT ($p<0.05$), was observed to have the closest value to the control in cooking yield (Table 4). Based on this result, the combination of low expressible fat and low-fat retention suggests that the complex cooking process leads to greater shrinkage and loss of both water and the less tightly bound gel-immobilized oil, ultimately reducing the product's final yield and fat retention more severely than predicted by basic stability metrics.

Table 4. Cooking characteristics of model meat emulsions

Treatments*	Moisture Retention (%)	Fat Retention (%)	PY (%)
CNT	55.55±0.02^{a}	87.56±0.04^{a}	89.71±0.04^{a}
GE50	43.21±0.67^{b}	74.97±1.16^{b}	66.53±1.03^{c}
GE75	37.51±0.36^{c}	71.70±0.68^{c}	63.05±0.60^{d}
GE100	43.88±0.13^{b}	58.41±0.89^{d}	70.18±0.21^{b}

*The treatments were formulated by: CNT: Standard-fat control (20% beef fat). GE50: 50% beef fat replacement with GE. GE75: 75% beef fat replacement with GE. GE100: 100% beef fat replacement with GE. a–d Different letters in the same column indicate significant differences ($p<0.05$).

Textural properties

The textural properties of foods are key quality parameters, dictating both sensory perception during consumption and product durability during transport and storage. Specifically for emulsified meat products (like sausages), texture is a critical quality indicator that depends on the batter structure, the amount of air incorporated, and the heat generated during mixing (Santhi et al., 2017; Yüncü-Boyacı et al., 2024). Several studies have demonstrated that replacing animal fat with vegetable oils can compromise the structural integrity of emulsified meat systems (Vural, 2003; Muguerza et al., 2004). The texture profile of the model meat emulsions was markedly affected by the incorporation of the gelled emulsion (Table 5).

The highest hardness value was determined in the CNT group ($p < 0.05$). This indicates the high resistance of the crystalline structure of solid fat at room temperature or under chilled conditions compared with the soft, gel-like matrix of the emulsions. The hardness values of the GE50, GE75, and GE100 groups were approximately four times lower than those of the CNT group ($p < 0.05$). This shows that GE significantly softens the overall matrix of the emulsion when used as a fat replacer. Similarly, researchers reported that the reduction in hardness and gumminess is attributed to the softer, gel-like matrix of GEs, which lack the rigid crystalline structure of solid fats (Wei et al., 2024; Zou et al., 2024; Zhang et al., 2025). In another study, the replacement of pork back fat with an emulsion composed of olive oil and soy protein isolate resulted in reduced hardness values, regardless of the emulsion level (20%, 25% or 30%) (Muguerza et al., 2001).

For springiness and cohesiveness, the highest values were observed in GE100 ($p <0.05$), with no significant difference found between the other groups and the CNT group $p > 0.05$). The gumminess values of the samples ranged from 2.07 N (GE75) to 7.61 N (CNT), indicating that the emulsions provide a less "gummy" mouthfeel. Full or high-level substitution (e.g., 100% EG) can maintain or even increase springiness and cohesiveness, likely due to the formation of a stable, elastic protein–polysaccharide network within the emulsion gel (Serdaroğlu et al., 2024; Yan & Zhang., 2025; Zhang et al., 2025).

Chewiness values, evaluated in parallel with hardness and springiness, showed no statistical difference between the CNT and GE100 groups ($p > 0.05$). A decrease in chewiness was observed when GE was used at 50% and 75% levels ($p < 0.05$). Chewiness generally decreases at partial substitution (50%-75%); however, it can be similar to control at 100% replacement, indicating that a well-formulated GE can closely mimic the textural profile of animal fat. Researchers have reported similar findings in their studies (Wei et al., 2024; Zou et al., 2024).

Table 5. Textural parameters of model meat emulsions

Treatments*	Hardness (N)	Springiness (mm)	Cohesiveness	Gumminess (N)	Chewiness (N.mm)
CNT	68.71±1.67^{a}	0.10±0.02^{b}	0.12±0.03^{b}	7.61±0.61^{a}	0.86±0.37^{a}
GE50	17.87±0.67^{c}	0.12±0.03^{b}	0.14±0.03^{b}	2.55±0.25^{bc}	0.31±0.10^{b}
GE75	22.32±1.51^{b}	0.11±0.02^{b}	0.12±0.02^{b}	2.07±0.45^{c}	0.21±0.04^{b}
GE100	17.17±0.79^{c}	0.32±0.13^{a}	0.19±0.02^{a}	3.07±0.38^{b}	0.95±0.34^{a}

*The treatments were formulated by: CNT: Standard-fat control (20% beef fat). GE50: 50% beef fat replacement with GE. GE75: 75% beef fat replacement with GE. GE100: 100% beef fat replacement with GE. a–c Different letters in the same column indicate significant differences ($p<0.05$).

Microstructure

The scanning electron microscopy (SEM) images of the model meat emulsions are presented in Figure 2. The presence of porous and fissured regions within the samples can adversely affect physical stability, while also providing valuable insight into several physicochemical characteristics (Cáceres et al., 2008). In the current study, the control samples formulated with 100% beef fat exhibited a less uniform and more irregular structure compared to the treatments containing GE. The incorporation of GE resulted in a smoother and more homogeneous matrix, indicating a more stable microstructural network. This observation aligns with findings from chia flour–based gelled emulsion utilized in beef patties, where GE addition effectively reduced structural voids and promoted a more compact appearance, particularly in formulations where animal fat was fully replaced (Serdaroğlu et al., 2024). Similarly, Moghtadaei et al. (2018) reported that replacing beef fat with sesame oil–based oleogel in burger patties produced a more compact and homogeneous structure compared to the control.

Consistent with these studies, the GE50 and GE75 samples in the present work displayed microstructures that visually resembled one another, suggesting that partial replacement of beef fat with gelled emulsion supports the formation of a more integrated and uniform matrix than that observed in the control formulation.

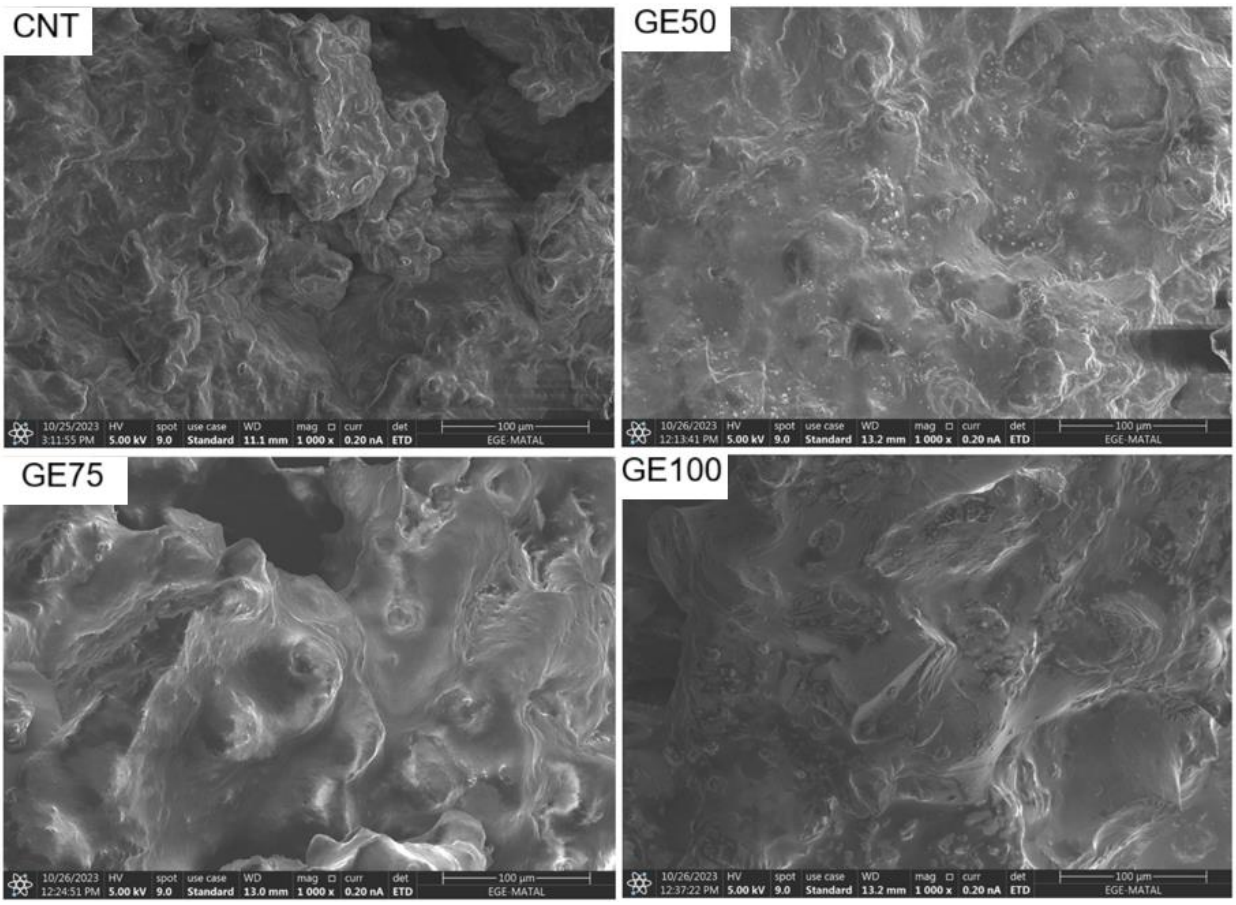

Figure 2. Microstructure of model meat emulsions. The treatments were formulated by: CNT: Standard-fat control (20% beef fat), GE50: 50% beef fat replacement with GE, GE75: 75% beef fat replacement with GE, GE100: 100% beef fat replacement with GE.

CONCLUSION AND RECOMMENDATIONS

This study investigated the effects of substituting beef fat with a chitosan-based gelled emulsion in model meat emulsions. The application of GE was found to improve the nutritional profile, particularly at the 50% replacement level, which exhibited the lowest fat content and the highest moisture/protein ratios. Although all reformulated samples increased total expressible fluid, GE100 showed the lowest fat exudation, indicating good stability before cooking. However, this high thermal stability did not translate into post-cooking performance; the GE groups displayed significantly lower processing yield, moisture, and fat retention compared to the control. Additionally, GEs resulted in higher jelly and fat separation compared to the control. Texturally, hardness and gumminess decreased as the GE ratio increased, while microstructural analyses revealed that the gelled emulsion formed a more homogeneous and smoother network in the meat matrix. In conclusion, the chitosan-based gelled emulsion offers potential for nutritionally improved products but requires further optimization, particularly to enhance stability during cooking and storage.

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