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Fat-reduced mayonnaise formulated with chia (*Salvia hispanica* L.) seed powder: Characterization, sensory evaluation, and rheological behavior

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ABSTRACT

Background and Purpose: This study aimed to evaluate the feasibility of incorporating whole chia seed powder as a functional replacer in mayonnaise. The effects of substituting 0 (control)–20% of the oil content with chia seed powder on physicochemical parameters (pH, emulsion stability, and peroxide value), rheological behavior, and sensory attributes (color, odor, taste, texture, and overall acceptability) were investigated to determine the optimal substitution level for maintaining product stability and consumer acceptance. Considering that chia is naturally rich in omega-3 fatty acids and other bioactive compounds, its incorporation also offers potential for the development of mayonnaise as a functional food product.

Materials and Methods: Mayonnaise formulations were prepared by replacing 0% (control), 5%, 10%, 15%, and 20% of the oil phase with chia seed powder. Samples were stored at 4 °C for 90 days. Physicochemical properties (pH, emulsion stability, and peroxide value), rheological parameters, and sensory attributes (color, odor, taste, texture, and overall acceptability) were evaluated at regular intervals.

Fundings: The addition of chia seed powders slightly increased pH values but within acceptable limits (pH≤ 4). Emulsion stability improved with increasing chia levels, that can be attributed to the chia mucilage. Rheological analysis confirmed shear-thinning flow (n<1) with increased viscosity at higher substitution levels, best described by the Herschel–Bulkley model. PV values increased significantly during storage; samples with up to 10% chia remained below the standard limit (≤2 meq O_2 /kg oil), whereas 15% and 20% exceeded this after 60 days due to the high poly unsaturated fatty acid (PUFA) content of chia. Sensory analysis showed that color scores declined with increasing chia, while taste and texture acceptability were negatively affected at ≥15%. Samples containing up to 10% chia maintained sensory scores comparable to the control.

Conclusion: Incorporating chia seed powder into mayonnaise improves emulsion stability, viscosity, and functional properties while contributing bioactive compounds. However, oxidative stability decreased at higher substitution levels, as elevated PUFA content outweighed the antioxidant effects of chia seed, leading to PV values above acceptable limits beyond 60 days. Sensory evaluation confirmed that substitution up to 10% provided acceptable outcomes in terms of taste, texture, and overall quality, comparable to the control. These findings suggest that whole chia seed powder can be effectively applied at ≤10% substitution as a functional ingredient to produce nutritionally enhanced mayonnaise without compromising safety, stability, or consumer acceptance.

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مایونز کم‌چرب فرموله شده با پودر دانه چیا (*Salvia hispanica* L.): تعیین خصوصیات، ارزیابی حسی و رفتار رئولوژیکی

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چکیده

سابقه و هدف: این پژوهش با هدف بررسی امکان استفاده از پودر کامل دانه چیا به‌عنوان یک ماده فراسودمند جایگزین چربی، در فرمولاسیون مایونز انجام شد. تأثیر جایگزینی (شاهد) ۰ تا ۲۰ درصد از مقدار چربی با پودر دانه چیا بر ویژگی‌های فیزیکوشیمیایی pH)، پایداری امولسیون و عدد پراکسید)، رفتار رئولوژیکی و شاخص‌های حسی (رنگ، بو، طعم، بافت و پذیرش کلی) ارزیابی شد تا بهترین سطح جایگزینی برای حفظ پایداری محصول و پذیرش مصرف‌کننده تعیین گردد. با توجه به این که دانه چیا به‌طور طبیعی غنی از اسیدهای چرب امگا-۳ و ترکیبات زیست‌فعال است، استفاده از آن می‌تواند به بهبود فرمولاسیون مایونز به‌عنوان یک فرآورده غذایی فراسودمند کمک کند.

مواد و روش‌ها: فرمولاسیون‌های مختلف مایونز با جایگزینی ۰ (شاهد)، ۵، ۱۰، ۱۵ و ۲۰ درصد از فاز روغن با پودر دانه چیا تهیه شدند. نمونه‌ها به مدت ۹۰ روز در دمای ٤ درجه سلسیوس نگهداری شدند و ویژگی‌های فیزیکوشیمیایی شامل pH، پایداری امولسیون و عدد پراکسید و همچنین شاخص‌های رئولوژیکی و ویژگی‌های حسی (رنگ، بو، طعم، بافت و پذیرش کلی) در فواصل زمانی منظم اندازه‌گیری شد.

یافته‌ها: افزودن پودر دانه چیا سبب افزایش جزئی در مقادیر pH شد؛ اما این مقادیر همچنان در محدوده قابل‌قبول ($pH \leq ٤$) باقی ماند. پایداری امولسیون با افزایش درصد پودر دانه چیا بهبود پیدا کرد؛ که این امر می‌تواند به حضور موسیلاژ دانه چیا نسبت داده شود. تحلیل رئولوژیکی نشان داد که همه نمونه‌ها رفتار رقیق شونده با برش ($n<1$) داشته و با افزایش سطح جایگزینی، گرانروی افزایش پیدا می‌کند. رفتار جریان کاملاً مطابق با مدل هرشل-بالکلی بود. مقادیر پراکسید در طول دوره نگهداری به‌طور معنی‌داری افزایش یافت ($p<0.05$). اما مقدار پراکسید نمونه‌های حاوی تا مقدار ۱۰ درصد پودر چیا تا پایان دوره نگهداری در محدوده استاندارد (≤ 2 meq O_2 /kg oil) باقی ماندند؛ درحالی‌که مقدار پراکسید نمونه‌های ۱۵ و ۲۰ درصد به دلیل محتوای بالای اسیدهای چرب غیراشباع موجود در پودر دانه چیا پس از ٦۰ روز فراتر از

حد مجاز قرار گرفتند. در ارزیابی حسی، امتیاز رنگ با افزایش سطح جایگزینی کاهش یافت و طعم و بافت در سطوح بیش‌تر از ۱۵ درصد جایگزینی، افت محسوس نشان داد. اما نمونه‌های حاوی تا مقدار ۱۰ درصد پودر دانه چیا از نظر حسی مشابه نمونه شاهد بودند.

نتیجه‌گیری: جایگزینی پودر دانه چیا در مایونز موجب بهبود پایداری امولسیون، افزایش گرانروی و ویژگی‌های عملکردی محصول می‌شود و درعین‌حال ترکیبات زیست‌فعال ارزشمندی را به فرمولاسیون وارد می‌کند. بااین‌حال، در سطوح بالاتر جایگزینی، پایداری اکسایشی کاهش می‌یابد و مقدار پراکسید پس از ۶۰ روز از حد قابل‌قبول فراتر می‌رود؛ زیرا محتوای بالای اسیدهای چرب غیراشباع، اثرات ضداکسایشی دانه چیا را تحت تاثیر قرار می‌دهد. یافته‌های حسی نشان دادند که جایگزینی تا سطح ۱۰ درصد، بدون ایجاد تغییرات نامطلوب در طعم، بافت و ارزیابی کلی، قابل‌قبول و مشابه نمونه شاهد است. بنابراین پودر کامل دانه چیا تا سطح ۱۰ درصد می‌تواند به‌عنوان یک ماده فراسودمند برای تولید مایونز با ارزش تغذیه‌ای بالا، مورد استفاده قرار گیرد، بدون‌آنکه به ایمنی، پایداری یا پذیرش مصرف‌کننده آسیب برساند.

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ناشر: دانشگاه علوم کشاورزی و منابع طبیعی گرگان

Introduction

In recent years, consumers have shown growing interest in the link between diet and health. As a result, the acceptance of food products depends not only on their quality and safety but also on their added health benefits. This has increased research into fortifying foods with functional ingredients [1].

Mayonnaise is one of the most widely consumed oil-in-water emulsions, commonly served with salads, sandwiches, and fast foods. Beyond its popularity, mayonnaise has increasingly been investigated as a carrier for functional ingredients, providing an opportunity to deliver health-promoting compounds through a familiar and widely accepted food matrix. Previous studies have examined the incorporation of seed powders into mayonnaise to improve stability and functionality. ShirMohammadi et al. (2015) evaluated the fortification of mayonnaise with flaxseed powder and showed that it improved the fatty acid profile and oxidative stability of the product [2]. Similarly, Fathi et al. (2021) showed that the addition of flaxseed powder improved the emulsion stability and viscosity of mayonnaise [3]. Özdemir et al. (2018) reported that black cumin seed powder enhanced the oxidative stability of mayonnaise but negatively influenced sensory acceptance at higher levels [4]. In another study, Pathak et al. (2020) demonstrated that fruit peel powders could act as natural stabilizers while providing additional bioactive compounds [5].

Chia (*Salvia hispanica* L.), a member of the Lamiaceae family, is cultivated worldwide and recognized as a valuable source of nutrients. Its seeds are rich in polyunsaturated fatty acids, especially α-linolenic acid (up to 68%), as well as dietary fiber, protein, bioactive peptides, polyphenols, antioxidants, vitamins, and essential minerals such as calcium, potassium, magnesium, and phosphorus. Numerous studies have reported that chia seeds may help reduce inflammation, act as antioxidants, and support cardiovascular, liver, and immune health [6]. Owing to these properties, chia is considered a promising functional ingredient for food applications [7–9]. Beyond its nutritional value, chia also provides technological benefits in food processing. When hydrated, the seeds form a mucilaginous gel that can serve as a texture modifier, thickener, stabilizer, emulsifier, bulking agent, encapsulating material, and edible coating in various formulations [10-13]. Chia oil is highly susceptible to oxidation due to its elevated content of polyunsaturated fatty acids, particularly α-linolenic acid (ALA, C18:3, ω-3). Exposure to oxygen, light, or elevated temperatures can rapidly accelerate lipid peroxidation, produce off-flavors and reduce nutritional quality. Therefore, without protective strategies such as microencapsulation or incorporation of antioxidants, the direct application of chia oil in food systems is limited. For this reason, its use is more suitable in products that are stored under refrigeration and protected from oxygen and light, rather than in formulations exposed to high temperatures or prolonged storage under ambient conditions [14].

Several studies have previously investigated the incorporation of chia-derived ingredients in mayonnaise formulations. Fernandes and Salas-Mellado (2018) demonstrated that partial replacement of oil or egg yolk with chia mucilage improved the physicochemical and sensory properties of mayonnaise, highlighting its potential as a fat replacer and stabilizer [9]. Odep et al. (2024) formulated low-fat and egg-free mayonnaise using a combination of chia mucilage and gum arabic, reporting enhanced emulsion stability, rheological behavior, and consumer acceptance [15]. In another study, Rahim et al. (2024) developed omega-3 enriched mayonnaise using spray-dried microcapsules containing blends of chia and fish oils. Their results showed that the microcapsules significantly improved oxidative stability while maintaining acceptable sensory characteristics [16]. Similarly, Rojas et al. (2019) reported that the inclusion of oil-loaded microparticles based on chia and pumpkin seed oils increased the viscosity and stability of mayonnaise [17]. Overall, these findings confirm that chia can be effectively applied in emulsion-based systems to enhance nutritional value, oxidative stability, and textural properties. However, despite these promising outcomes, there is still limited information on the direct application of whole chia seed powder as a partial oil replacer in mayonnaise formulations. Therefore, the aim of this study was to assess the feasibility of replacing 0% (control), 5%, 10%, 15%, and 20% of the oil content in mayonnaise with whole chia seed powder to improve product quality and explore its potential as a functional food.

Materials and Methods

Materials

Chia (*Salvia hispanica* L.) seeds were purchased from Zarrin Nuts Trading Company and milled using a bench- top grinder (1000 W, 20000 rpm) for 4 min in short pulses to avoid overheating. The ground material was then passed through a 60-mesh sieve (≈250 µm) to remove coarse hull fragments and obtain a uniform powder, suitable for emulsion systems. The sieved powder was packed in opaque, airtight containers and stored at 4 °C until use. All chemical material and reagents used in this study were of analytical grade and obtained from certified commercial suppliers.

Mayonnaise preparation

Mayonnaise was prepared according to a modified standard procedure. Egg (12%) was first blended for 30 s using a kitchen mixer (Bosh, E-Nr. MFQ 1501, Type HR 12 ST, Germany). Salt (1.25%), sugar (3.25%), citric acid (0.1%), sodium benzoate (0.06%), mustard powder (0.34%), vinegar (7%), and water (11%) were then added and mixed at speed 1 for 5 min. Whole chia seed powder was incorporated at levels of 5%, 10%, 15%, and 20% (based on sensory analysis, data were not presented) of the oil phase prior to oil addition. Finally, sunflower oil (65%) was gradually added and emulsified for 10 min at speed 2, followed by 5 min of mixing at speed 3. The prepared mayonnaise samples were transferred into 100 mL screw-cap glass bottles and stored at 4 °C for subsequent analyses [18].

pH Measurement

The pH of mayonnaise samples was measured following the procedure described by Mirzanajafi-Zanjani et al. (2019) with slight modifications [19]. Briefly, 10 g of mayonnaise was homogenized with 90 mL of distilled water (1:10, w/v) for 1 min using a laboratory mixer. The pH of the homogenized suspension was then determined at room temperature (25 ± 1 °C) using a digital pH meter (86502 AZ, Taiwan, TES), previously calibrated with standard buffer solutions at pH 4.0 and 7.0.

Emulsion stability

Mayonnaise samples (m_0 = 15 g) were transferred into 50 mL centrifuge tubes and centrifuged (Biofuge, Heraeus 3335, Germany) at 3500 rpm for 30 min [18]. After centrifugation, the separated top oil layer was carefully removed, and the lower sedimented layer was considered as the precipitated fraction, was then weighed (m_1), and the stability of each sample was calculated according to Equation (1):

$$\text{Stability (\%)} = (m_1 / m_0) \times 100 \qquad \text{(Eq. 1)}$$

Rheological properties

Rheological measurements were carried out using a rheometer (Anton-Paar rheometer, Physica MCR51) equipped with a temperature control system (water circulator) and cone–plate geometry (cone angle 1°, gap 0.01 mm). Each sample was placed between the cone and plate and allowed to rest for 5 min to recover its structure. Measurements were performed at 25 °C in both rotational and oscillatory modes. Apparent viscosity was determined over a shear rate range of 0.1–100 s^{-1}. For dynamic testing, an oscillatory strain sweep was first conducted to determine the linear viscoelastic region (LVR). A strain of 1% (within the LVR) was selected for the frequency sweep, which was carried out over a frequency range of 0.1–100 Hz. Storage modulus (G′), loss modulus (G″), and loss tangent (tan δ) were recorded.

Flow curves were fitted to the Power law ($\tau = K \gamma^n$) and Herschel–Bulkley ($\tau = K.\gamma^n + \tau_0$) models for data analysis. where, τ is the shear stress (Pa), τ_0 is the yield stress (Pa), K is the consistency index (Pa·s), γ is the shear rate (s^{-1}), and n is the flow behavior index (dimensionless).

Color of mayonnaise

The color of mayonnaise samples was measured using a Hunter-Lab Colorflex Colorimeter (Hunter Associated Lab, Inc., Reston, Virginia, USA), against a white and black tiles standards. A fixed amount of mayonnaise sample was placed in the measurement glass cup. The cup placed above the light source, covered with black cap and Hunter values (*L**, *a**, *b**) were measured.

Peroxide value (PV)

Initially, the mayonnaise samples were stored in a freezer at -18 °C overnight. After freezing, the samples were thawed at room temperature in the dark to destabilize the emulsion. The samples were then centrifuged at 9000 rpm for 15 min. The extracted oil was collected and stored in brown bottles with screw caps at -18 °C. The peroxide value (PV) of the extracted oil was determined according to the AOCS Official Method Cd 8-53.

Sensory evaluation

Sensory evaluation was carried out with 20 semi-trained panelists (10 males and 10 females, aged 20–55) recruited from students and staff of the Faculty of Agriculture. All participants were screened to ensure the absence of allergies to the ingredients used in mayonnaise and were trained in preliminary sessions to assess sensory attributes. Each panelist received 5 g of mayonnaise in transparent plastic cups, with water and toasted bread provided for palate cleansing between samples. A nine-point hedonic scale (1 = dislike extremely, 9 = like extremely) was used to evaluate odor, taste, color, texture, and overall acceptability [4].

Statistical Analysis

The experiment was arranged in a completely randomized design (CRD) with five treatments (0%, 5%, 10%, 15%, and 20% chia seed powder substitution) across four storage times (0, 30, 60, and 90 days), each performed in triplicate. Data were analyzed using two-way analysis of variance (ANOVA) to evaluate the effects of substitution level and storage time, as well as their interaction, on the measured parameters. Mean comparisons were performed using Duncan's multiple range test (DMRT) at a significance level of $p < 0.05$. Statistical analyses were carried out with Minitab version 16.00 (Minitab Inc., State College, PA, USA).

Results and Discussion

pH

For microbiological safety, the pH of mayonnaise should be maintained below 4.1, a condition typically achieved by the inclusion of vinegar (acetic acid) and other acidifying agents such as citric acid. The pH also plays a crucial role in determining the viscoelasticity and stability of oil-in-water emulsions. Maximum stability is usually observed when the pH is close to the average isoelectric point of proteins (≈ 4.0), due to the minimization of electrostatic repulsion and optimal protein–oil interactions [4, 20].

As shown in Figure 1, the incorporation of chia seed powder resulted in a slight but consistent increase in pH values during storage. This trend can be attributed to the intrinsic composition of chia. Chia proteins and minerals (e.g., Ca, Mg, K, and phosphates) provide buffering groups that partially neutralize acetic acid in the aqueous phase, thereby shifting the apparent pH upward. Beyond the higher initial pH from chia's buffering, the slight rise during storage reflects matrix effects: gradual hydration of chia mucilage and ion exchange release alkaline minerals that partially neutralize acetic acid. In parallel, redistribution and minor headspace loss of acetic acid reduce the effective acidity of the continuous phase, so the measured pH drifts slightly upward over time [21]. Despite this increase, all mayonnaise samples remained below the safety threshold of pH 4.1 for at least 60 days of refrigerated storage, ensuring microbiological stability. Comparable findings have been reported for mayonnaise enriched with ginger extract (Kishk & Elsheshetawy, 2013) and emulsions fortified with herbal additives (Drozłowska et al., 2020), where the buffering and antimicrobial characteristics of plant-derived components influenced the pH dynamics of the system [22, 23].

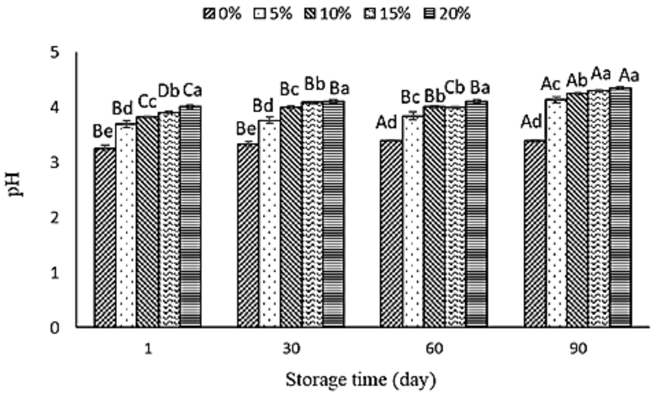

Figure 1. The pH values of mayonnaise samples containing different levels of chia seed powder during 90 days of storage at 4 °C.

Lowercase letters and uppercase letters indicate significant differences ($p< 0.05$) among different samples at the same storage time and across different storage times for the same samples, respectively.

Stability

According to Figure 2, the emulsion stability of the mayonnaise samples containing various amounts of chia seed powder was significantly higher ($p< 0.05$) than that of the control during the 90 -day storage period at 4 °C. A decrease in emulsion stability with increasing storage time was observed in all samples. Low stability in the control mayonnaise may result from oil droplet coalescence due to insufficient amounts of thickening agents or stabilizers. In contrast, in the chia-containing samples, chia mucilage acted as a natural thickening and stabilizing agent, increasing the viscosity of the aqueous phase, which restricted droplet mobility and delayed coalescence. Similar findings were reported by Park et al. [18] for starch-based mayonnaise, where stabilization was attributed to hydrocolloid interactions. Previous studies have also confirmed that plant mucilages possess strong thickening and gelling properties that enhance emulsion stability and rheological behavior in food systems [10, 19, 24, 25].

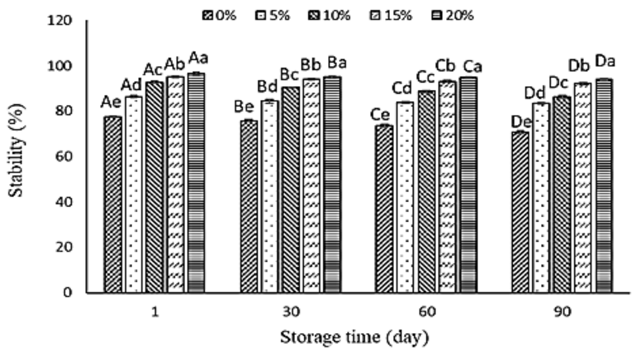

Figure 2. Stability of mayonnaise samples containing different levels of chia seed powder during 90 days of storage at 4 °C.

Lowercase letters and uppercase letters indicate significant differences ($p < 0.05$) among different samples at the same storage time and across different storage times for the same samples, respectively.

Rheological properties

The rheological characterization of mayonnaise provides valuable insight into its structure–function relationships, which are critical for texture, stability, and consumer perception. In this study, all formulations displayed non-Newtonian, shear-thinning behavior (Figure 3), a typical property of oil-in-water emulsions, where apparent viscosity decreases with increasing shear rate due to droplet alignment and the disruption of weak flocculated networks [19, 26].

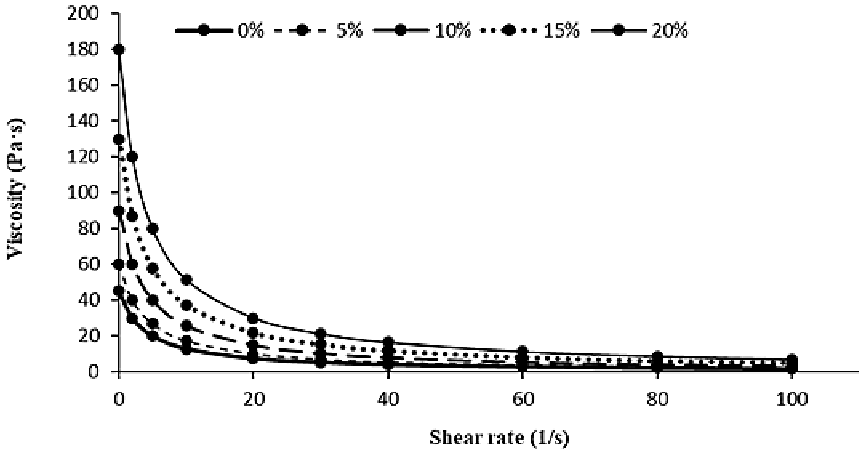

Figure 3. Apparent viscosity (Pa·s) as a function of shear rate (1/s) for mayonnaise samples prepared with different levels of chia seed powder.

Increasing the level of fat replacement with chia seed powder significantly enhanced the consistency of the emulsions, as reflected by higher apparent viscosity and increased consistency coefficient, while the flow behavior index (n = 0.2–0.4) remained below 0.6, confirming pronounced pseudoplasticity (Table 1). These results are consistent with studies on mayonnaises formulated with starch, flaxseed mucilage, and oat β-glucan, all of which reported higher viscosity and stronger shear-thinning compared with full-fat controls [18, 19, 23, 24].

The flow curves of mayonnaise samples were fitted to both the Power law and Herschel–Bulkley models (Table 1). In the Power law model, the flow behavior index (n) ranged from 0.17 to 0.30, confirming pronounced shear-thinning (pseudoplastic) behavior. The consistency coefficient (K) increased from 56.78 Pa·s in the control to 112.23 Pa·s at 20% replacement, indicating higher apparent viscosity with increasing chia concentration. However, the model provided moderate fits (R^2 = 0.92–0.96).

In contrast, the Herschel–Bulkley model gave superior fits ($R^2 \geq 0.99$), highlighting the presence of a measurable yield stress (τ_0), which rose from 27.77 Pa for the control to 67.80 Pa for the 20% sample. This increase suggests that higher concentrations of chia seed powder reinforce the emulsion network, requiring greater stress to initiate flow. The consistency coefficient (K) also increased (16.40 → 36.43 Pa·s), while the flow behavior index (n = 0.3–0.5) remained below unity, confirming pseudoplasticity. These results demonstrate that the Herschel–Bulkley model ($R^2 \geq 0.98$) better represents the rheological behavior of chia-based reduced-fat mayonnaises than the Power law ($R^2 \leq 0.96$), due to its ability to capture both shear-thinning behavior and yield stress, consistent with previous studies on hydrocolloid-stabilized emulsions [26-28].

Table 1. Flow behavior parameters of mayonnaise samples fitted to the Power law and Herschel–Bulkley models

Replacement (%)	Yield stress	Consistency coefficient, K (Pa·s)	Flow behavior index, n	R^2
Power law model				
0%(Control)	-	56.78	0.17	0.96
5%	-	57.60	0.17	0.95
10%	-	78.50	0.19	0.92
15%	-	99.11	0.2	0.92
20%	-	112.23	0.3	0.94
Herschel–Bulkley model				
0% (Control)	27.77	16.40	0.30	0.98
5%	34.44	19.16	0.40	0.99
10%	45.73	20.91	0.4	0.99
15%	65.33	23.90	0.4	0.99
20%	67.80	36.43	0.5	0.99

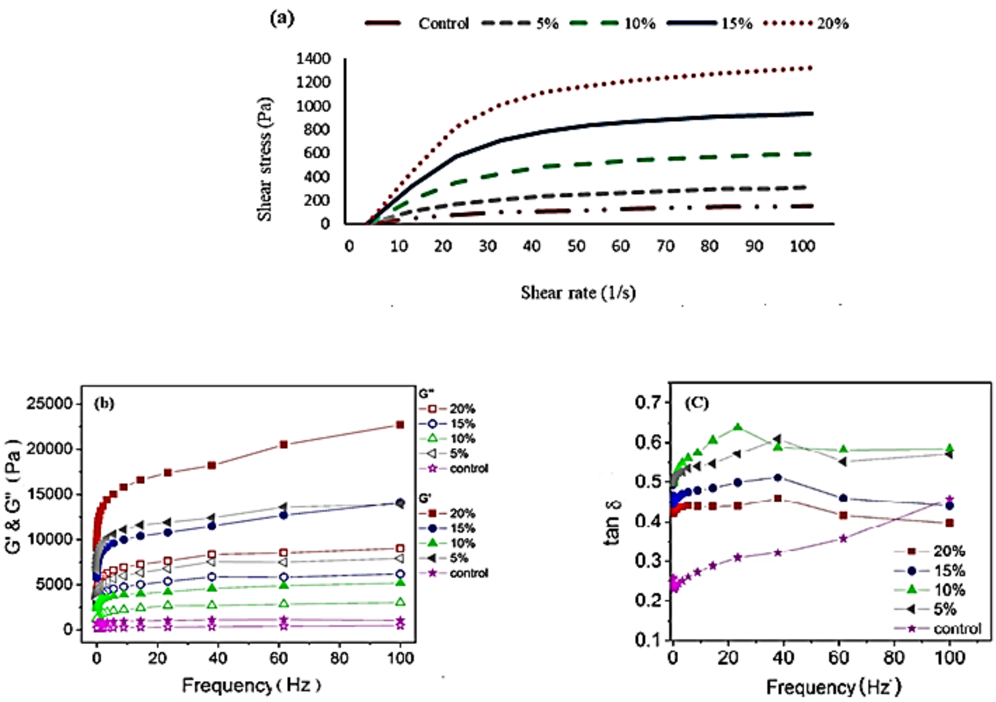

Figure 4. Rheological parameters of mayonnaise samples containing different levels of chia seed powder (0%,5%, 10%, 15%, 20%) and control: (a) Shear stress as a function of shear rate (s^{-1}); (b) Storage modulus (G′) and loss modulus (G″) as functions of frequency (Hz); (c) Loss tangent (tan δ) as a function of frequency.

The results of the oscillatory rheological analysis are presented in Figure 4. The incorporation of chia seed powder markedly increased both storage modulus (G′) and loss modulus (G″), with G′ consistently exceeding G″ at frequencies above 0.1 Hz, demonstrating weak gel-like structures dominated by elastic contributions. This behavior, also reported for reduced-fat emulsions thickened with hydrocolloids, is attributed to the formation of a three-dimensional polysaccharide network that enhances water binding and droplet immobilization [18]. The ratio of viscous to elastic response (tan δ) remained below unity in all formulations, decreasing as chia content increased, which highlights a progressive shift toward more elastic and solid-like behavior. Such gel-like characteristics are advantageous for spreadability, mouthfeel, and stability against coalescence, in agreement with previous research on hydrocolloid-enriched mayonnaises [24, 27].

Taken together, these results clearly demonstrate that chia seed powder functions not only as a fat replacer but also as a rheological modifier that reinforces the viscoelastic structure of mayonnaise. By increasing viscosity, enhancing shear-thinning behavior, strengthening the viscoelastic network, and reducing tan δ, chia contributes to desirable texture and stability. These findings provide strong evidence that plant-derived hydrocolloids can be effectively exploited to design reduced-fat emulsions with improved technological properties [24, 27, 28].

Color parameters

Color represents one of the most critical qualitative attributes of mayonnaise, as it strongly influences consumer perception and overall acceptability of the product [24, 27]. Figure 5 illustrates the color parameters of mayonnaise samples formulated with different levels of chia seed powder during storage. Significant differences ($p < 0.05$) were observed in the L^*, a^*, and b^* values among the samples. In contrast, no significant differences were observed the same samples during storage time ($P > 0.05$). The control sample exhibited the highest lightness ($L^* = 79.50 \pm 0.14$), while the formulation containing 20% chia seed powder showed the lowest value ($L^* = 65.15 \pm 0.08$). This decrease in lightness can be attributed to the naturally dark color of chia seed powder, which reduces the brightness of the final product. Similar findings have been reported for full-fat mayonnaise, where L^* values typically range from 61 to 89 depending on formulation methods and droplet size distribution [24, 27, 28].

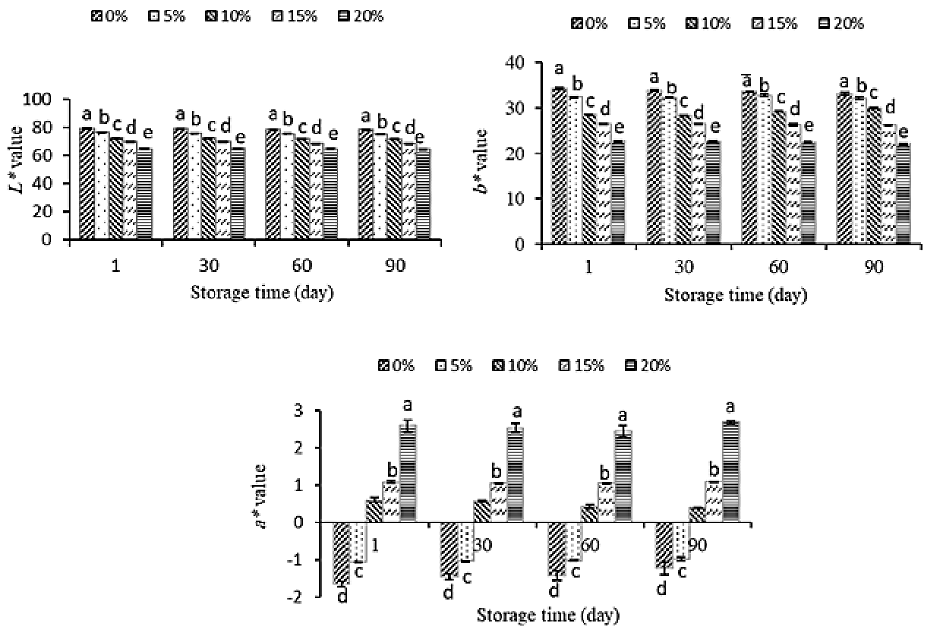

Figure 5. Color parameters of mayonnaise samples containing different amounts of chia seed powder during 90 days storage at 4 °C.

Lowercase letters indicate significant differences ($p < 0.05$) among samples at the same storage time.

Substitution of fat with chia seed powder resulted in a significant ($p < 0.05$) increase in redness (a^*) and a decrease in yellowness (b^*). Comparable trends were reported by Park et al. [18], who observed increased a^* and decreased b^* values when fat was replaced with starch. Likewise, Chang et al. [27] demonstrated that the use of fat replacers led to a reduction in b^* values in mayonnaise. Carcelli et al. [28] also noted that mayonnaise enriched with β-glucan appeared paler due to reduced oil content, as oil contributes to the characteristic yellow color. Overall, these findings highlight that different fat replacers and hydrocolloid-based ingredients possess distinct light-scattering properties, which in turn influence the *L**, *a**, and *b** values of mayonnaise formulations.

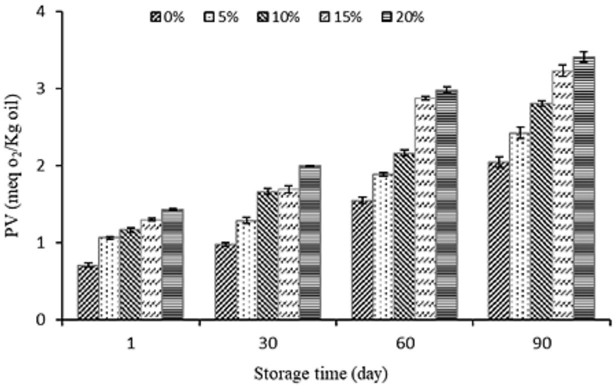

Figure 6. Peroxide value of mayonnaise samples containing different levels of chia seed powder during 90 days of storage at 4 °C.

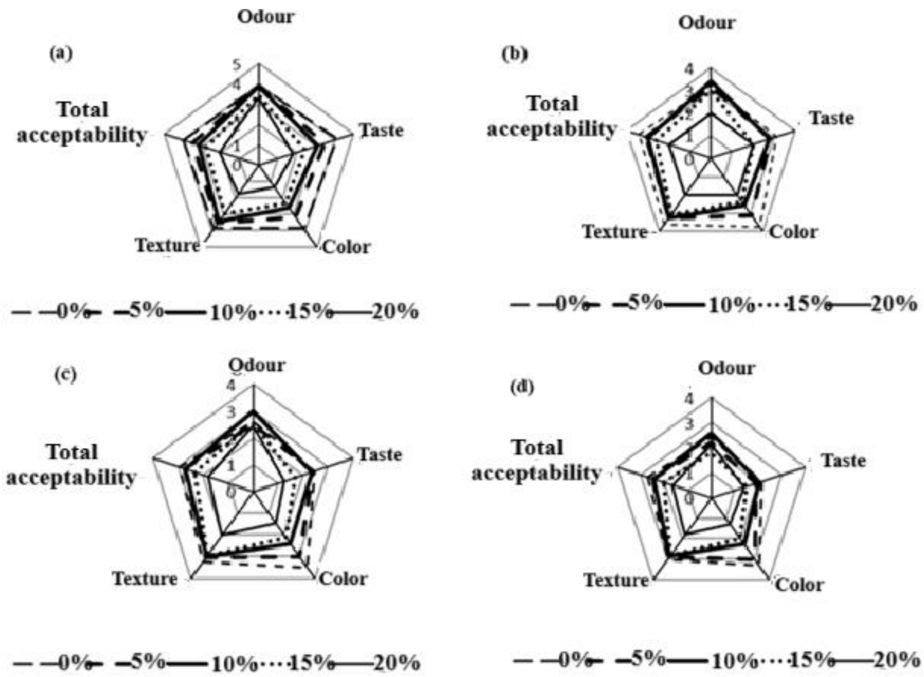

Figure 7. Sensory attributes of mayonnaise samples formulated with different levels of chia seed powder during storage at 4 °C. a-d: day 1, 30, 60, and 90, respectively

Lipid oxidation

As shown in Figure 6, peroxide values increased during storage for all formulations. According to Codex and national standards, the acceptable PV limit for mayonnaise is ≤ 2 meq O_2 /kg oil [29, 30]. In the present study, samples containing up to 10% chia seed powder remained within this limit throughout 90 days of storage, while formulations with 15% and 20% substitution exceeded the threshold after 60 days. This behavior can be attributed to the lipid composition of chia seed powder, although it provides natural antioxidants such as tocopherols and polyphenols [13, 14], it is also extremely rich in polyunsaturated fatty acids, particularly α-linolenic acid (C18:3, ω-3), which is highly susceptible to oxidation [11]. The presence of these fatty acids likely outweighed the antioxidant effect at higher replacement levels, resulting in accelerated hydroperoxide formation. Overall, these findings suggest that moderate incorporation of chia seed powder (≤10%) supports oxidative stability within the regulatory limit, whereas higher levels compromise long-term stability due to enhanced susceptibility to lipid peroxidation.

Sensory evaluation

The results of the sensory evaluation of mayonnaise prepared with different concentrations of chia seed powder during a 90-day storage period at refrigerated condition are presented in Figure 7 (a-d). Overall, all sensory attributes gradually declined during storage, except for color. Furthermore, increasing the chia seed powder concentration generally reduced sensory scores, although odor scores were slightly higher in the 5% and 10% formulations. This effect may be linked to the high phenolic content of chia seed powder, which can impart bitterness and astringency. Similar findings were reported by Özdemir et al. who observed reduced acceptability in mayonnaise enriched with black cumin oil due to its phenolic constituents [4]. Mirzanajafi-Zanjani et al. (2019) also reported that flaxseed mucilage could be successfully incorporated into mayonnaise at moderate substitution levels, while higher levels led to a decline in sensory acceptability [19]. In emulsified systems such as mayonnaise, phenolic compounds can interact with both the aqueous and oil phases, influencing flavor perception and overall acceptability [4, 38]. In this study, formulations containing up to 10% chia seed powder maintained sensory properties closest to the control sample, while higher substitution levels had a more negative impact on consumer acceptance.

Conclusion

This study demonstrated the potential of chia seed powder as a functional fat replacer in mayonnaise. Partial substitution of oil with chia seed powder improved emulsion viscosity, stability, and rheological behavior, confirming the thickening and structuring role of chia-derived hydrocolloids. Moreover, the presence of natural antioxidants in chia contributed to delaying lipid oxidation at moderate substitution levels; however, at higher concentrations (15 and 20%), the high content of polyunsaturated fatty acids, particularly α-linolenic acid, increased susceptibility to oxidation, leading to elevated peroxide values during storage. Sensory evaluation further revealed that while incorporation of 15% and 20% negatively affected taste and texture acceptability, formulations containing up to 10% chia seed powder maintained sensory properties comparable to the control. Overall, these findings indicate that the application of chia seed powder at levels of up to 10% of the oil phase can be recommended as an effective strategy to produce reduced-fat, stable, and functionally enhanced mayonnaise.

Limitations of this study include use of a single chia source and evaluation under refrigerated storage only. Future work should verify these findings with different chia materials and processing conditions, assess shelf life and safety more comprehensively, and confirm consumer acceptance in larger panels.

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