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Physicochemical, Rheological, and Sensory Characterization of Pistachio–Pumpkin Seed Composite Pastes

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Abstract

This study investigated the physicochemical, rheological, and sensory characteristics of composite pastes formulated with pistachio kernel paste (PKP) and pumpkin seed paste (PSP) at varying ratios: 100:0, 0:100, 90:10, 80:20, 70:30, 60:40, and 50:50 (w/w). Rheological behavior was evaluated using Power-law, Herschel–Bulkley, Bingham, and Casson models. The Herschel–Bulkley model provided the most accurate fit for Samples 1–6 (R^2 = 0.9844–0.9999), exhibiting pseudoplastic shear-thinning behavior with flow behavior index (n) values ranging from 0.6919 to 0.8773. Sensory evaluation using a 5-point hedonic scale by 20 trained panelists demonstrated that the 70:30 (PKP:PSP) formulation achieved the highest overall acceptability score without compromising textural stability. These results establish the optimal blending ratio for developing shelf-stable, functional nut-seed spreads with desirable rheological and sensory attributes.

Keywords: valorization; seed paste; rheological modeling; shear-thinning behavior; functional spread

1. Introduction

In recent decades, the global health-oriented trend has changed the pattern of food consumption, in such a way that the focus has shifted from the mere supply of energy to the use of "functional foods". Meanwhile, nuts and oilseeds play an undeniable role in the prevention of chronic diseases, including cardiovascular disorders, obesity, and metabolic syndromes, due to their dense nutritional profile including high-quality proteins, unsaturated fatty acids (MUFA and PUFA), antioxidant compounds (such as tocopherols and phytosterols), and essential micronutrients [1–5]. As a strategic product, pistachio (*Pistacia vera* L.) has optimal amounts of lipids (40–60%) and protein (17–20%), along with impressive biological activity and processing dynamics, and has a high potential for use in new formulations [1–3,6]. At the same time, pumpkin seeds (Cucurbita sp.) as a nutraceutical source with significant protein content (28–36%) and rich in minerals (zinc, magnesium and phosphorus) have attracted the attention of researchers as an economical and nutritious alternative or supplement. Economically, incorporating pumpkin seeds as a widely cultivated and cost-effective ingredient may offer a practical approach to diversify pistachio-based formulations while maintaining desirable paste structure [4,5,7].

The production of nut pastes through mechanical processes such as milling is more than a simple physical change. This process requires careful engineering of the "food matrix" to establish stability [1,8,9]. The commercial development and consumer acceptability

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of nut and seed pastes depend fundamentally on their structural integrity, flow behavior, and oral mouthfeel, which are governed by the continuous lipid phase and dispersed solid particles. While long-term physical stability and colloidal phenomena have been recognized as broader technological considerations in nut butters, understanding the primary rheological fingerprint, yield stress, and sensory mouthfeel resulting from matrix blending constitutes the critical initial step. Therefore, establishing how varying proportions of pumpkin seed paste alter the flow resistance, thixotropy, and sensory attributes of pistachio paste is essential for designing cohesive plant-based spreads. The rheological behavior of paste, especially the non-Newtonian (pseudoplastic) and thixotropic characteristics, directly affects the quality of processability (such as filling and pumping) and the quality of sensory perception (mouthfeel) [10–16]. Therefore, achieving an optimal consistency that has favorable "spreadability" and maintains its structural stability over time is a technological necessity for the industrial production of these products [17–21].

Although nut and seed butters/pastes have been widely studied as fat-continuous dispersions with strong structure–texture relationships, reports addressing the systematic blending of different nut and seed matrices and quantifying how blend ratio modulates physicochemical and rheological properties remain limited. In particular, information on composite pastes combining pistachio kernel paste with pumpkin seed paste is scarce [11–15,21]. Therefore, the present study focuses on characterizing how increasing pumpkin seed paste proportion affects key quality-related properties of pistachio-based composite pastes. From a nutritional standpoint, blending pumpkin seeds with pistachio kernels is conceptually supported by the literature, as both matrices naturally contribute complementary unsaturated lipid fractions and plant proteins, offering potential for nutrient-dense formulation. However, the balance between the ratio of these two components in the paste matrix is highly sensitive and can strongly affect the viscosity and oxidative stability of the product [17–21].

From a practical point of view, the development of texture-modified foods is one of the current priorities of the food industry for the aging population. Common problems in the elderly, such as swallowing difficulties or chewing problems, have increased the need for "Nutrient-dense" products but with soft texture and easy swallowing [2,22–24]. Although nut-based pastes are inherently attractive to this group, to be considered a "geriatric-specific" product, they must have certain rheological properties (such as controlled stickiness and viscosity suitable for swallowing) [25–28]. Although the current research focuses on the general panel, the data obtained from the rheological and sensory characteristics of this paste provide a scientific basis for future research in the direction of developing special texture-modified products for the elderly [2,18,23,25–31].

Due to the limitation of existing knowledge about the characteristics of pistachio–pumpkin seed mixed paste, the main goal of this research is comprehensive physicochemical, rheological characterization and sensory evaluation of this product in different mixing ratios. This research seeks to answer the key question of how replacing pistachios with pumpkin seeds affects textural characteristics and consumer acceptance. The results of this study provide a practical framework for the design of sustainable and economic formulations and will lay the groundwork for the development of a new generation of multipurpose pastes [17–21].

2. Materials and Methods

2.1. Raw Materials

The raw materials used in this research included pistachio nuts (*Pistacia vera*) and pumpkin seed nuts (*Cucurbita pepo*), which were obtained from the local market of Kerman, Iran. After manual separation of wastes and damaged seeds, the samples were packed in

impermeable nylon bags to maintain nutritional quality and prevent lipid oxidation and were kept at refrigerator temperature until the beginning of the experiments.

2.1.1. Physicochemical Properties

The physicochemical characteristics of pistachio nuts, pumpkin seeds and the oils extracted from them were investigated as basic factors in the formulation. These characteristics include true density, viscosity, specific gravity, refractive index, total protein, crude fat, ash, crude fiber, carbohydrates, moisture content (as a key factor in paste durability and texture), iodine value, soap value, acid value, peroxide value, and the amount of unsaponifiable matter, which was measured based on international standard methods (1).

2.1.2. Sample Preparation

In order to improve the flavor characteristics, inactivate the decomposing enzymes and facilitate the grinding process to achieve the appropriate soft texture, pistachio kernels and pumpkin seed kernels without shell were roasted separately in a convection oven (UNB 500, Memmert, Schwabach, Germany) at a temperature of 130 °C for 35 min. After cooling the samples at room temperature, the pistachio thin shell was separated manually.

2.1.3. Formulation and Preparation of Paste Mixtures

Formulations were designed with the aim of optimizing nutritional properties and creating a uniform and ingestible texture. Pistachio nuts and pumpkin seeds were mixed in specific weight ratios (Table 1). The resulting suspension was ground in a laboratory colloidal mill (Model MKZA6-5, Masuko Sangyo Co., Ltd., Kawaguchi, Japan) at a speed of 1000 rpm in order to obtain a stable emulsion and a completely soft and spreadable paste texture. Figure 1 shows the production and evaluation process of pistachio–pumpkin seed paste.



Figure 1. Schematic representation of the production and evaluation process of pistachio–pumpkin seed paste.

Table 1. Pistachio kernel—pumpkin seed paste formulations used in this study.

Samples	Pistachio Kernel Paste (%)	Pumpkin Seed Paste (%)
1	100	0
2	0	100
3	90	10
4	80	20
5	70	30
6	60	40
7	50	50

2.1.4. Sensory Evaluation

Considering the importance of sensory acceptance of soft foods in the diet of the elderly, the sensory evaluation of the samples was performed using a 5-point hedonic scale (1 = very unfavorable, 5 = very favorable). The characteristics of flavor, texture and color were evaluated as key factors of consumer acceptance. In order to select panelists, a triangular screening test was conducted on volunteers in the age range of 25 to 40 years, and finally 20 trained panelists (12 women and 8 men) were selected. Samples (~15 g) were presented in identical containers coded with randomized three-digit codes. The serving order was randomized across panelists to eliminate presentation order bias. Sensory evaluation was performed in triplicate, so that each panelist tested 2 samples daily for 3 days of the week. In order to prevent the interference of flavors, the panelists washed their mouths with clean water before testing each sample. All tests were performed under standard temperature conditions (22 ± 1 °C) and under white fluorescent light [2–8].

2.1.5. Rheological Properties

The measurement of rheological properties, which play a vital role in evaluating the ease of swallowing and the flow of paste in the mouth, was performed using a Bohlin Visco 88 rotary viscometer (Bohlin Instrument, Cirencester, U.K.) equipped with a bob and cup system (bob length 60 mm, bob diameter 14 mm, and gap distance 1 mm) connected to a temperature-controlled hot water bath (model F12-MC, Julabo Labortechnik, Seelbach, Germany). Bohlin v 06.32 software was used to record and process shear stress and shear rate data. Flow curves were drawn at a constant temperature with a gradual increase in shear rate from 120 to 1400 s^{-1} over a period of 800 s.

Additionally, the apparent viscosity was evaluated at a representative shear rate of 40 s^{-1}, which falls within the characteristic oral shear rate range (40–50 s^{-1}) widely recognized for the sensory and masticatory evaluation of high-consistency semi-solid nut and seed pastes [22].

To describe the steady-shear flow behavior of the pistachio–pumpkin seed paste formulations, experimental shear stress (σ, Pa) versus shear rate ($\dot{\gamma}$, s^{-1}) flow curves (ascending shear rate sweep) were fitted to four widely accepted non-Newtonian rheological models:

1. Power Law (Ostwald–de Waele) Model:

$$\sigma = K \cdot \dot{\gamma}^{n}$$

where K is the consistency index ($Pa \cdot s^{n}$) and n is the flow behavior index (dimensionless). A value of $n < 1$ indicates pseudoplastic (shear-thinning) behavior.

2. Herschel–Bulkley Model:

$$\sigma = \sigma_0 + K_{HB} \cdot \dot{\gamma}^{n_{HB}}$$

where σ_0 is the yield stress (Pa), K_{HB} is the consistency coefficient ($Pa \cdot s^{n_{HB}}$), and n_{HB} is the flow behavior index.

3. Casson Model:

$$\sigma^{0.5} = \sigma_{0c}^{0.5} + K_c \cdot \dot{\gamma}^{0.5}$$

where σ_{0c} is the Casson yield stress (Pa) and K_c is the Casson plastic viscosity ($Pa^{0.5} \cdot s^{0.5}$).

4. Bingham Plastic Model:

$$\sigma = \sigma_{0B} + \eta_p \cdot \dot{\gamma}$$

where σ_{0B} is the Bingham yield stress (Pa) and η_p is the Bingham plastic viscosity ($Pa \cdot s$).

Non-linear regression fitting was conducted using MATLAB R2017a. The goodness-of-fit of the rheological models was evaluated based on the coefficient of determination (R^2).

The viscosity reported in Table 2 was the apparent viscosity measured at a shear rate of 40 s^{-1} under the specified measurement temperature. The Bohlin Visco 88 instrument calculated the apparent viscosity from the measured shear stress and shear rate according to the relationship $\eta_{app} = \tau/\dot{\gamma}$, where η_{app} is the apparent viscosity (Pa·s), τ is the shear stress (Pa), and $\dot{\gamma}$ is the shear rate (s^{-1}). The value at 40 s^{-1} was obtained directly from the instrument software after conversion to cP, using 1 Pa·s = 1000 cP. The reported values were rounded according to the measurement precision and are presented as mean ± standard deviation of the replicate measurements.

Table 2. Proximate composition and physicochemical characteristics of the raw starting materials (pistachio kernels, pumpkin seeds, and their extracted oils).

Physicochemical Properties	Pumpkin Seed/Oil	Pistachio Kernel/Oil
Crude protein%	32.33 ± 0.15 [a]	25 ± 0.09 [b]
Crude fat/oil%	34.71 ± 0.31 [b]	55.55 ± 0.10 [a]
Ash%	3.54 ± 0.11 [a]	3.17 ± 0.07 [a]
Crude fiber%	6.11 ± 0.19 [b]	18 ± 0.22 [a]
Total carbohydrate	21.85 ± 0.15 [a]	16.22 ± 0.12 [b]
Moisture content%	5.00 ± 0.03 [a]	4.5 ± 0.01 [a]
Refractive index (25 °C)	1.4659 ± 0.01 [a]	1.4696 ± 0.002 [a]
Specific Gravity	0.914 ± 0.02 [a]	0.923 ± 0.005 [a]
Iodine Value (g I_2/100 g oil)	103.73 ± 0.14 [a]	94.79 ± 0.91 [b]
Saponification value (mg KOH/g Oil)	187.20 ± 0.21 [a]	185.93 ± 2.03 [a]
Acid value (mg KOH/g Oil)	0.65 ± 1.02 [a]	0.18 ± 0.1 [b]
Peroxide value (meq peroxide/kg oil)	0.42 ± 0.28 [a]	0.21 ± 0.03 [b]
Apparent viscosity at 40 s^{-1} (cP)	93.66 ± 0.19 [a]	59.71 ± 0.09 [b]
Unsaponifiable matter content (%)	5.73 ± 0.21 [a]	5.93 ± 0.14 [a]
True Density (kg/m^3)	1161.01 ± 1.01 [a]	1085.39 ± 0.57 [b]

Different lowercase superscript letters in the same column indicate statistically significant differences among the treatments based on Tukey's test ($p < 0.05$).

2.1.6. Statistical Analysis of Data

A completely randomized design (CRD) was employed with seven formulations containing different pistachio kernel paste (PKP) to pumpkin seed paste (PSP) ratios: 100:0, 0:100, 90:10, 80:20, 70:30, 60:40, and 50:50 (w/w). All physicochemical and rheological measurements were performed in triplicate ($n = 3$), and sensory evaluation was conducted using a 5-point hedonic scale with 20 trained panelists. Experimental data were subjected to one-way analysis of variance (ANOVA) to assess significant differences among treatments. Differences between treatment means were evaluated using Tukey's post hoc test at a 95% confidence level ($p < 0.05$). Descriptive statistics and ANOVA were carried out using Minitab 16, and GraphPad Prism 6.07 was used for graphical visualization. Nonlinear regression modeling and determination of the coefficients of determination (R^2) for the rheological models were performed using MATLAB software (version R2017a, The MathWorks, Inc., Natick, MA, USA).

3. Results

3.1. Baseline Composition and Physicochemical Attributes of Raw Materials

Table 2 summarizes the proximate composition and physicochemical characteristics of the raw pistachio kernels, pumpkin seeds, and their extracted lipid fractions prior to paste formulation. The raw kernels exhibited high lipid and protein contents, confirming their suitability as high-density matrices for spread development. Furthermore, the low free fatty acid levels and peroxide values of the extracted oils indicated good initial oxidative quality of the starting materials. These baseline characteristics served to standardize the raw ingredients before blending into the composite pastes evaluated in the subsequent rheological and sensory trials. The results of the evaluation of the physicochemical characteristics of pistachios and pumpkin seeds showed that these two raw materials have significant differences from each other in terms of some compositional and functional indicators (Table 2). Specifically, the amount of protein and carbohydrates in pumpkin seeds was significantly higher than pistachios ($p < 0.05$). This finding shows that pumpkin seeds have a significant ability to participate in the enrichment of formulations in terms of the composition of macronutrients, especially in the field of protein density. In contrast, pistachio showed lower values in terms of these two indicators, but this does not necessarily mean its lower value in the formulation, because the role of each raw material in a food system is not limited to only one or two composite indicators and must be interpreted in the context of a set of nutritional, sensory and functional characteristics. Also, the true density of pumpkin seeds was significantly higher than that of pistachios ($p < 0.05$). This difference can indicate a more compact structure and a different arrangement of solid components in the texture of the raw material. From the point of view of food technology, the change in the true density can affect the behavior of the material in the stages of mixing, grinding, and paste formation, as well as the final characteristics of the product, including the consistency, texture, and even the uniformity of the system. Therefore, the difference observed in this index is not just a numerical difference, but can also play a role in explaining part of the rheological and sensory differences in different formulations. On the other hand, some of the characteristics measured between the two raw materials did not show significant differences ($p > 0.05$). These indicators included ash, moisture content, refractive index, specific gravity, saponification value, and unsaponifiable matter. The absence of significant differences in these variables indicates that pistachios and pumpkin seeds are relatively similar in some general chemical and oil aspects. On the one hand, this similarity can facilitate the process of combining these two materials, and on the other hand, it can show that the main differences between them are manifested in more specific variables such as protein, carbohydrate, density, and some oil indicators.

In the section related to the oil extracted from these two raw materials, significant differences were also observed. According to the data in Table 2, iodine value, acid value, peroxide value and apparent viscosity in pumpkin seed oil were significantly higher than in pistachio oil ($p < 0.05$). The increase in iodine value in pumpkin seed oil indicates that this oil probably has a higher degree of unsaturation. From a nutritional point of view, this can be seen as a desirable feature, as unsaturated fatty acids are usually associated with better nutritional value. However, the simultaneity of this feature with the increase in peroxide value and acid value can indicate the greater sensitivity of this oil to oxidation and degradation. The higher peroxide value in pumpkin seed oil shows that this oil has a weaker condition in terms of oxidative stability compared to pistachio oil. Likewise, an increase in acid value can indicate a higher degree of hydrolysis or the release of free fatty acids. On the other hand, the higher apparent viscosity of pumpkin seed oil also shows that this oil has a different flow behavior than pistachio oil, and this difference can affect the overall behavior of the final paste system. Overall, the findings of this section show that

pistachios and pumpkin seeds have important differences not only in terms of macronutrient composition, but also in terms of oil characteristics, and these differences can affect the nutritional properties, stability and physical characteristics of the final paste.

3.1.1. Sensory Evaluation of Pistachio–Pumpkin Paste

The sensory evaluation results showed that the mixing ratio of pistachios and pumpkin seeds has a significant effect on the sensory characteristics of the final paste (Figure 2). In a direct comparison between two pure samples, the color score in pure pumpkin seed paste was significantly higher than in pure pistachio paste ($p < 0.05$). This result shows that pumpkin seeds, in terms of appearance color, convey a characteristic to the product that was more favorable for sensory panelists. Since color is one of the first characteristics perceived by the consumer when encountering the product, a significant difference in this attribute can play an important role in the initial acceptance of the samples.

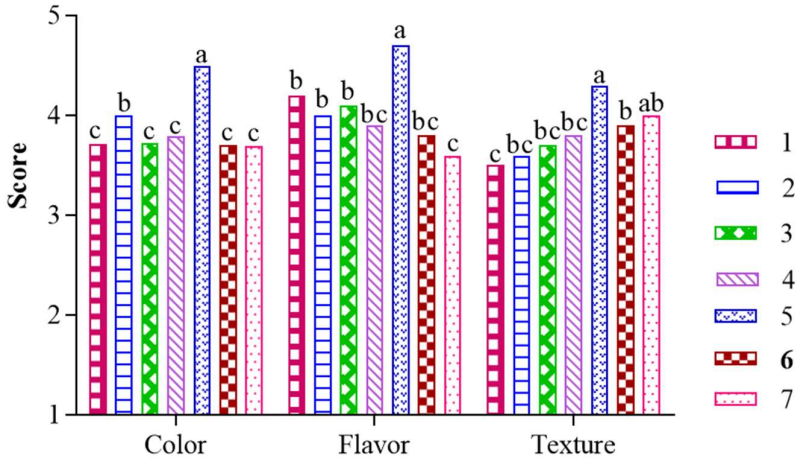


Figure 2. Sensory properties of pistachio kernel—pumpkin seed pastes. Different lowercase superscript letters in the same column indicate statistically significant differences among the treatments based on Tukey's test ($p < 0.05$).

On the other hand, the flavor score and texture score between pure pistachio paste and pure pumpkin seed paste did not show a significant difference ($p > 0.05$). This finding shows that although the two primary ingredients were different from each other in terms of chemical composition and oil characteristics, in the form of pure paste, their difference in terms of flavor and texture perception was not enough to be recorded as a significant difference in sensory evaluation. This result is very important because it shows that pumpkin seeds can be used in formulations at some replacement levels, without significant loss in some key sensory attributes.

The trend of changes in sensory scores in mixed samples showed that by increasing the share of pumpkin seeds to 30%, scores related to color, flavor, and texture increased. This increase shows that the addition of pumpkin seeds at low to medium levels can have a synergistic effect on some sensory aspects of the product and lead to a more favorable balance between appearance, flavor and texture characteristics. However, after passing the level of 30% and in the range of 30–50%, a decrease in sensory scores was observed. This pattern indicates that the effect of pumpkin seeds on the sensory characteristics is not linear and uniform, but has an optimal level, after which the dominance of the specific characteristics of this component can reduce acceptability.

Among all tested formulations, the composite paste containing 70% pistachio and 30% pumpkin seed paste obtained the highest mean sensory scores across the evaluated attributes (color: 4.50 ± 0.18, flavor: 4.70 ± 0.15, and texture: 4.30 ± 0.20), which was

significantly higher ($p < 0.05$) than formulations with higher pumpkin seed substitution (30–50%). Although sample 4 (80% pistachio/20% pumpkin seed) exhibited lower apparent viscosity and yield stress, panelists favored the richer body and cohesive mouthfeel of the 70:30 formulation. These scores demonstrate baseline palatability within a young adult cohort; however, this hedonic pattern should not be extrapolated as verified acceptance by geriatric consumers. The range of scores recorded for different attributes also showed that color score ranged from 3.69 to 4.50, flavor score ranged from 3.60 to 4.70, and texture score ranged from 3.510 to 4.30. These ranges show that although the differences in the sensory scale were relatively limited, these differences were sufficient to distinguish between the samples and determine the optimal formulation. In general, the results of this section show that pumpkin seeds, if used in the right proportion, can be used in the formulation of pistachio paste without losing sensory quality and even with the improvement of some attributes.

3.1.2. Rheological Characteristics of Pistachio–Pumpkin Paste

Examining the rheological behavior of the paste samples showed that all the studied formulations follow non-Newtonian and clearly pseudo-plastic behavior (Figure 3). As depicted in Figure 3, the experimental flow data (symbols) were fitted to the Herschel–Bulkley model (solid lines), demonstrating excellent agreement across the entire shear rate range (120–1400 s^{-1}). This means that with the increase in the shear rate, the apparent viscosity of the system decreases and the product behaves more smoothly under the conditions of applying force. Such a pattern is observed in many pastes and semi-solid food systems, and in terms of processing and consumption, it is usually considered a desirable feature. Because the product shows less resistance to flow when stirred, pumped, filled or even consumed, while at rest it maintains its consistency to some extent.

To describe the flow behavior of the formulated pastes, experimental shear stress–shear rate data were fitted to common rheological models (Power-law, Bingham, Casson, and Herschel–Bulkley) (30). Among the evaluated models, the Herschel–Bulkley model provided the most robust description of the experimental flow curves across all formulations, yielding high coefficients of determination with R^2 ranging from 0.9844 to 0.9999 (Table 3). Although simpler two-parameter models such as the Power-law were evaluated for baseline comparison, the pronounced curvature of the flow curves at low shear rates, quantified by the systematically superior goodness-of-fit of yield-stress models over yield-free models (Table 3), indicated a finite yield threshold. This behavior was mathematically well accommodated by the yield stress parameter (τ_0) in the Herschel–Bulkley and Casson models, conferring superior numerical fitting compared with models lacking a yield parameter. Nevertheless, complementary oscillatory or creep-recovery measurements would be valuable in future work to physically validate the true microstructural yield stress.

Analysis of the Herschel–Bulkley model parameters indicated that the flow behavior index (n) ranged between 0.6919 and 0.8773 ($n < 1$), confirming the pseudoplastic (shear-thinning) nature of all formulations. As the proportion of pumpkin seed paste increased, a gradual decrease in n and a corresponding increase in the consistency coefficient (K, ranging from 0.216 to 10.530 Pa · s^n) were observed (Table 3). Furthermore, the magnitude of yield stress (τ_0) varied between 48.35 and 271 Pa, reflecting structural changes in the particle network upon blending the two seed matrices.

In accordance with the model fitting, the apparent viscosity (measured at the reference shear rate) exhibited values ranging from 3.68 to 9.84 Pa · s (Figure 3). While a slight initial variation was observed from 10% to 20% pumpkin seed substitution, higher inclusion levels (20% to 50%) systematically enhanced apparent viscosity and structural stiffness, which is consistent with the higher solids and consistency index of the blended matrices.

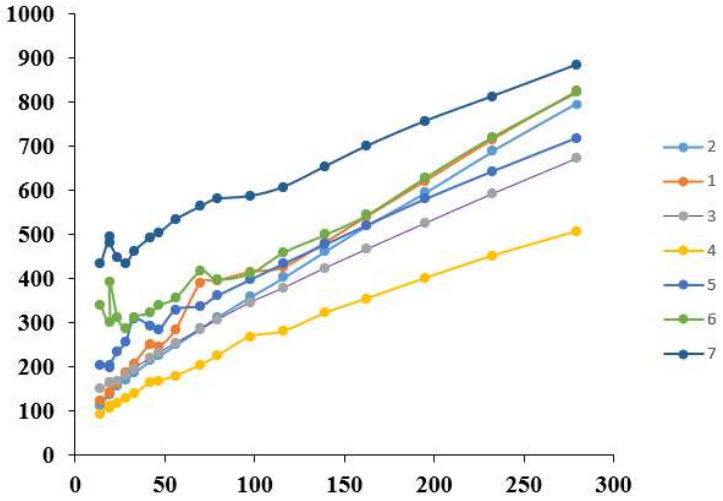


Figure 3. Flow curves (shear stress vs. shear rate) of pistachio–pumpkin seed paste formulations. Symbols represent the experimental data points, and the continuous solid lines represent the non-linear regression curves predicted by the Herschel–Bulkley model ($\tau = \tau_0 + k\dot{\gamma}^n$) using the model parameters reported in Table 3.

Table 3. Statistical parameters of the time-independent rheological models determined for flow curves of pistachio–pumpkin seed paste *.

Model/Sample		1	2	3	4	5	6	7
Power-law	k	31.53	12.45	23.54	13.55	49.74	57.59	84.58
	n	0.561	0.737	0.5927	0.6416	0.473	0.4617	0.4095
	R^2	0.9951	0.9958	0.9913	0.9947	0.9748	0.9151	0.9727
Herschel–Bulkley	τ_0	96.95 ^{d}	61.99 ^{e}	99.43 ^{d}	48.35 ^{f}	165.7 ^{c}	271 ^{a}	211.1 ^{b}
	k	10.53 ^{b}	5.216 ^{d}	5.476 ^{d}	5.421 ^{d}	6.683 ^{c}	8.7422 ^{b}	13.25 ^{a}
	n	0.731 ^{c}	0.8773 ^{a}	0.8238 ^{a}	0.7868 ^{b}	0.7849 ^{b}	0.7163 ^{c}	0.6919 ^{c}
	R^2	0.9999	0.9989	0.9997	0.9980	0.9902	0.9850	0.9844
	η ^{a}	6.33 ^{c}	4.87 ^{d}	5.34 ^{d}	3.68 ^{e}	7.17 ^{b}	9.84 ^{a}	9.53 ^{a}
Casson	k_0	83.18	28.96	61.90	35.22	119.8	138.1	184.1
	k	1.084	1.36	1.072	0.9877	0.9504	0.9722	0.9468
	R^2	0.9995	0.9989	0.9996	0.9979	0.9897	0.9597	0.9854
Bingham	τ_0	175.4	96.38	139.9	89.05	215.9	244.6	301.2
	k	2.023	2.496	1.89	1.491	1.817	1.951	2.045
	R^2	0.9899	0.9969	0.9956	0.9919	0.9838	0.9816	0.9717

* Values represent the estimated model parameters ($n = 3$). Different lowercase superscript letters in the same column indicate statistically significant differences among the treatments based on Tukey's test ($p < 0.05$).

This nonlinear behavior once again shows that the rheological response of the paste to the change in mixing ratio is not simple and uniform. It seems that at low substitution levels, pumpkin seed may facilitate relative movement of system components, while at higher levels, its structural role dominates and increases flow resistance. This issue is very important from the point of view of product design, because it shows that choosing the right mixing ratio can lead to the precise adjustment of the consistency and flowability of the product.

On the other hand, the flow curves obtained from the ascending and descending shear-rate sweeps displayed enclosed hysteresis loops, with the enclosed loop area tending to be more noticeable in the composite formulations (Figure 4a–c). In continuous shear flow, such hysteresis loops reflect shear-history dependence and shear-induced structural breakdown during continuous deformation. It should be emphasized that, in this study, the ascending and descending limbs were not modeled separately, nor was structural regeneration kinetics quantitatively evaluated. Therefore, the observed hysteresis loops provide qualitative evidence of time-dependent structural breakdown rather than a complete

kinetic characterization of thixotropy. Dedicated structural-kinetics modeling, structural-recovery tests (such as three-interval thixotropy tests), and stress-relaxation measurements represent valuable directions for future investigations. This feature can affect the behavior of the product during processing as well as the sensory perception of the consumer. In general, the results of this section show that the mixing ratio of pistachios and pumpkin seeds has a direct effect on the characteristics of flow, consistency and time stability of the paste, and these parameters can be used to choose a more appropriate formulation.

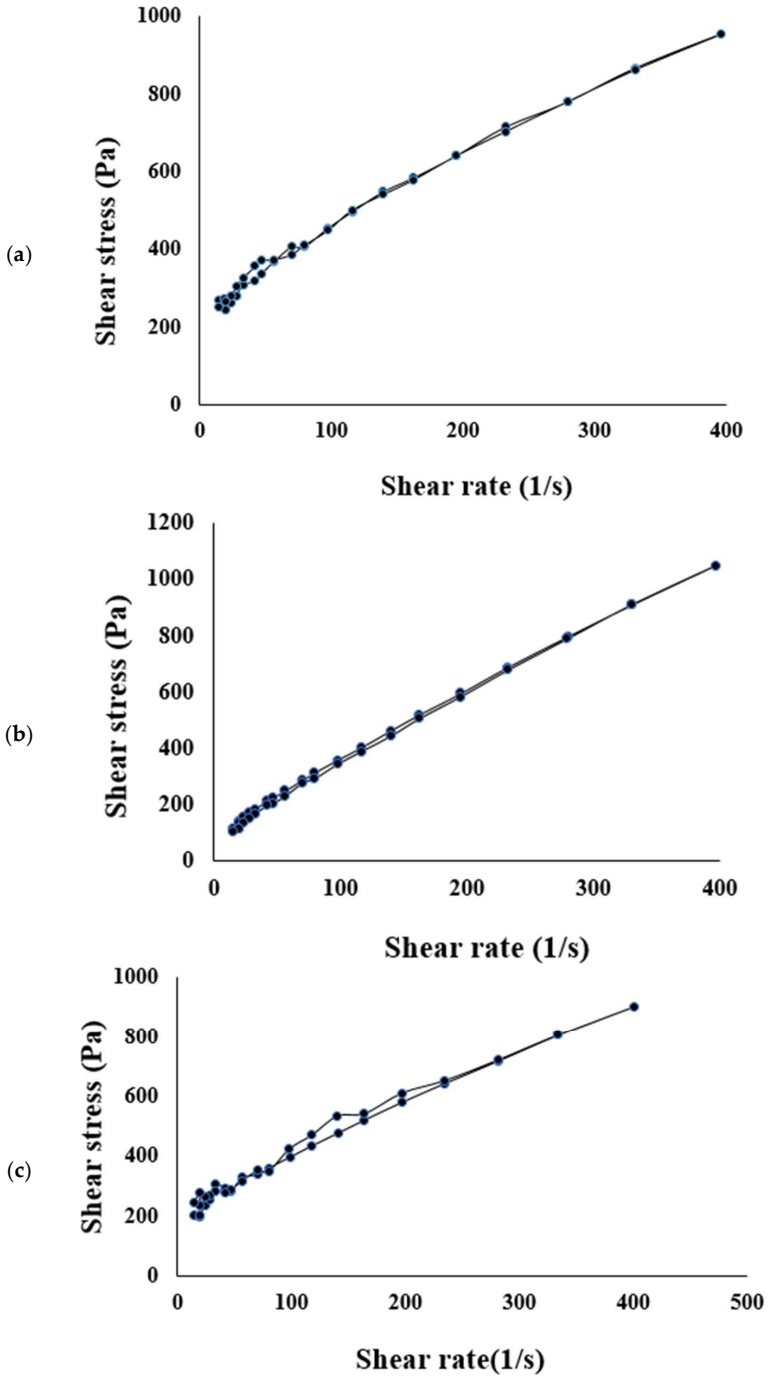


Figure 4. Hysteresis loop of the flow curves of pistachio kernel—pumpkin seed pastes: (**a**) pistachio paste, (**b**) pumpkin seed paste, (**c**) pistachio—pumpkin seed paste (70–30%).

Furthermore, while the formulation concept relies on the recognized nutrient density of the raw kernels, specific chromatographic profiling of fatty acids (GC-FID) and amino

acids (HPLC), along with rigorous techno-economic evaluation and life-cycle assessment (LCA), were outside the empirical scope of this initial rheological investigation and warrant dedicated future study.

4. Discussion

The pronounced shear-thinning (pseudoplastic) behavior observed across all formulations ($n < 1$) holds critical technological relevance for oral processing and consumer perception. During mastication and oral transit, the shear rates generated between the tongue and the hard palate typically range between 10 and 100 s^{-1} (commonly approximated at ~ 50 s^{-1}). At these physiological shear rates, the rapid disruption of the internal colloidal network significantly lowers apparent viscosity, facilitating effortless spreadability in the oral cavity and reducing perceived heaviness. Furthermore, the presence of an initial yield stress ensures that the paste maintains dimensional stability and resistance to gravitational sagging at rest, yet yields smoothly under oral shear. Although such rheological attributes are frequently highlighted in texture engineering as desirable mechanical foundations for soft and easily manipulated food matrices, their actual performance under specialized physiological conditions requires further dedicated oral-tribological and sensory characterization.

On the other hand, the higher values of iodine value, acid value and peroxide value in pumpkin seed oil show that this oil is more unsaturated and more sensitive to oxidation. This finding is doubly important in terms of product production for the elderly, because this age group may be more sensitive to the unpleasant sensory quality caused by oxidation, such as the aftertaste, and any loss of quality can reduce their food acceptance. In addition, in the formulation of special products for the elderly, oxidative stability is important not only in terms of shelf life, but also in terms of maintaining nutritional and sensory quality. Therefore, if this paste is to be developed for the consumption of the elderly in the future, the use of strategies such as optimization of packaging, control of storage conditions and possibly the use of permitted food antioxidants should be considered.

From a sensory point of view, the results showed that changing the ratio of pistachios and pumpkin seeds has an effect on the overall acceptance of the product, and the optimal formulation can benefit from the combined benefits of both raw materials without a sharp drop in acceptability. This matter is important because, in the design of food for the elderly, only the appropriateness of the texture is not enough and sensory acceptance, especially flavor, aroma and mouthfeel, plays an important role in the continuation of consumption and adequate intake of energy and nutrients. Previous studies have also shown that pumpkin seeds, if used in a controlled formulation, can be present in food products with favorable acceptance [2–4]. However, in the elderly population, it should be noted that decreased sense of flavor and smell, dry mouth and greater sensitivity to sticky or heavy textures may change the sensory perception of the product; therefore, the acceptance observed in this study cannot be generalized to the elderly without specific evaluation.

The shear-thinning behavior observed across all formulations ($n < 1$) indicates that apparent viscosity decreased as shear rate increased. This behavior is consistent with the disruption and alignment of structural elements under shear and may support spreadability [27,28]. The superior fit of the Herschel–Bulkley model suggests that the pastes exhibit yield-stress behavior, although the model fit alone does not establish the microstructural origin of that behavior [27,32,33]. The larger hysteresis loop area observed in the pumpkin-seed-rich formulations suggests a greater sensitivity to shear-history-dependent structural breakdown during continuous shearing. However, confirming structural recovery kinetics requires dedicated time-dependent recovery tests in future studies [34]. These properties may influence oral processing and structural recovery; however, their

implications for safe swallowing or suitability for older adults cannot be established from rheological measurements alone and require appropriate sensory and swallowing-related assessment [33,35].

Overall, the present findings show that the pistachio–pumpkin seed paste has a suitable capacity to be developed as a nutritious product, and some of its characteristics, such as the shear-thinning behavior and higher protein content in samples containing pumpkin seeds, can be attractive from the perspective of elderly nutrition. From a formulation standpoint, combining pistachio and pumpkin seed pastes produces a composite matrix characterized by high solids, substantial plant-based protein content, and a fat-continuous network. In contemporary food structuring, these nutrient-dense plant matrices are widely investigated for their ability to deliver sustained energy and essential macronutrients in a highly cohesive and compact format. The blend of 70:30 (pistachio to pumpkin seed paste) exhibited a favorable balance between structural yield stress, moderate flow resistance, and sensory harmony, making it a promising system for spreadable plant-based applications. While the current findings establish the physical and mechanical baseline for these blended matrices, comprehensive evaluation across broader consumer demographics and specialized texture-tailored dietary segments remains a valuable avenue for future exploration. The increase in apparent viscosity and thixotropic loop area observed in blended pastes can be attributed to the high protein and fiber content of pumpkin seed paste. The increase in apparent viscosity and thixotropic loop area observed in blended pastes can be attributed to the high protein and fiber content of pumpkin seed paste. As demonstrated in previous studies [33,35], incorporation of seed matrices introduces active hydrophilic and lipophilic functional groups that enhance particle-particle friction and structural resistance during shearing, thereby modulating spreadability and structural recovery.

It should be noted that while the present work provides detailed steady-shear and sensory characterization of the composite pastes, microstructural attributes such as laser diffraction particle-size distribution and accelerated oil separation (syneresis) during prolonged storage were not monitored. These parameters represent pertinent physical criteria for shelf-life estimation and warrant dedicated focus in subsequent storage stability trials.

Several methodological and technological boundaries of the present work must be acknowledged. First, sensory screening was conducted with a healthy adult panel (aged 25–40 years) to establish baseline formulation palatability; targeted sensory and texture acceptability trials directly involving older adults or clinical cohorts are essential to establish demographic-specific adoption. Second, while the flow curve parameters demonstrated robust shear-thinning characteristics, the elevated yield stress highlights that swallowing safety cannot be inferred without standardized clinical evaluations (e.g., IDDSI funnel and fork-drip tests, videofluoroscopy). Finally, future investigations should evaluate long-term colloidal stability, oil syneresis kinetics during storage, and particle size distribution (PSD) to optimize commercial shelf life and swallowing dynamics.

5. Conclusions

In total, the results of this research showed that replacing a part of pistachio with pumpkin seeds can lead to significant changes in the physicochemical and rheological characteristics of the paste without completely removing the sensory acceptability. The increase in protein and carbohydrate content, changes in flow and consistency indicators, as well as differences in oil characteristics, all indicate that pumpkin seeds can be used as a valuable functional and nutritional component in the formulation of these types of products. Based on this, the optimal formulation obtained in this study has the potential to develop a nutritional product with tunable textural properties. From a practical point of view, this capacity can be considered in the design of special products for sensitive groups,

including the elderly. The shear-thinning behavior may contribute to improved ease of consumption, and the higher protein content of formulas containing pumpkin seeds is also of potential importance in terms of nutritional support, especially in relation to maintaining muscle mass in old age. However, due to the individual differences in the elderly in terms of oral condition, chewing ability, swallowing performance and clinical conditions, it is not possible to make a definite conclusion about the suitability of this product for all the elderly based on the present findings alone. Therefore, it is suggested that in future studies, additional evaluations in the field of texture, swallowing ability, sensory acceptance in the elderly population, and compliance with standards such as IDDSI should be carried out in order to enable a more accurate determination of the position of this product in the nutrition of the elderly.

Also, due to the greater sensitivity of pumpkin seed oil to oxidation, it is necessary to check the oxidative stability and shelf life of the product in different storage conditions. Finally, it can be concluded that pistachio–pumpkin seed paste is a promising option for the development of innovative and nutritious products, but its targeted use for the elderly will require additional evidence and further optimization of formulation and textural properties.

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