Structural and rheological behaviour of mayonnaise-type emulsions containing aquafaba and functional oil blends

Yana Svishchova[1], Anastasiia Sachko[2], Sergii Gubsky[1], Olena Stabnikova[3], Octavio Paredes-López[4]

1 – State Biotechnological University, Kharkiv, Ukraine
2 – Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine
3 – National University of Food Technologies, Kyiv, Ukraine
4 – National Polytechnic Institute, Cinvestav, Irapuato, Guanajuato, Mexico

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Corresponding author:

Olena Stabnikova
E-mail:
stabstab6@gmail.com

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Abstract

Introduction. This study examined the potential of aquafaba as a plant-based emulsifier in low-fat mayonnaise sauces prepared with blended oils.

Materials and methods. The oil phase was prepared from blends of sunflower and hemp oils, with the addition of black cumin oil. Aquafaba obtained from industrially boiled beans was used as a natural emulsifier. The sauces were characterized through sensory evaluation, structural analysis, and rheological measurements using laser diffraction and viscometry.

Results and discussion. The effect of blended vegetable oils (hemp and black cumin) and aquafaba on the sensory, rheological, and structural properties of mayonnaise-type sauces was examined. Incorporation of blended oils at specific ratios enhanced the flavor profile by lowering acidity and imparting characteristic spicy notes. At hemp oil contents up to 25%, a high degree of homogenization and uniform particle size distribution of the dispersed phase were observed. Higher levels of α-linolenic acid in the oil phase increased emulsion polydispersity and promoted floc formation, as indicated by a higher flocculation index, irregular particle distribution, and greater surface area of the fat phase.

Laser diffraction and microscopy revealed that ultrasonic treatment reduced average droplet size and narrowed size distribution, resulting in greater system homogeneity, as evidenced by lower flocculation index and polydispersity values across all sauces. Rheological analysis using the Ostwald–de Waele and Casson models confirmed pseudoplastic behavior in all systems and demonstrated that rheological properties were dependent on the composition of the oil phase.

Sauces containing more than 75% sunflower oil exhibited similar rheological characteristics. Viscosity and ultimate shear stress increased with higher hemp oil content, while greater flocculation reduced structural compactness and stability. The sauce with the highest hemp oil content demonstrated pronounced thixotropy and a high structural recovery coefficient.

Conclusions. Incorporating aquafaba with blended oils makes it possible to create stable emulsions that not only remain consistent over time but also demonstrate enhanced functional and technological qualities.

Introduction

Food emulsions play a significant role in the food industry. One of the most popular emulsions is mayonnaise, a widely used sauce in various culinary applications. In traditional formulations, emulsifiers are primarily animal-derived proteins (Urbánková et al., 2019; Vathsala et al., 2023), along with plant-based stabilizers and thickeners, including gums, starch, and pectin. The use of mixed ionic and non-ionic surfactants as emulsifiers has also been reported (Mikulcová et al., 2017). However, the increasing demand for plant-based mayonnaise alternatives has encouraged the substitution of animal ingredients with plant-derived components. Such reformulations not only lower the caloric content (Huang et al., 2022; Stabnikova & Paredes-López, 2024) and reduce product allergenicity (Gómez-Candela et al., 2011; Sarkar et al., 2020), but also enhance microbiological safety. Plant-based emulsifiers that may be employed include sucrose palmitate (Jufret et al., 2022), quinoa and amaranth proteins (Gürbüz et al., 2018), tea saponins (Usman et al., 2025), sesame protein isolate (Niazi et al., 2025), a range of unconventional plant proteins isolated from green biomass, leaves, and grasses (Gubsky et al., 2025), as well as aquafaba proteins (Sachko et al., 2023).

Utilizing by-products from plant processing to improve food quality is a sustainable strategy for converting agricultural residues into value-added products (Mironeasa et al., 2024; Stabnikova et al., 2023a, b). For example, aquafaba, the liquid obtained from cooked chickpeas, can be repurposed from waste into a functional ingredient owing to its valuable protein and polysaccharide content. The quantitative characteristics of aquafaba are strongly influenced by the legume variety and processing conditions, including cooking time, legume-to-water ratio, temperature, pressure, pH, and salt content (Schmidt et al., 2023).Aquafaba proteins are mainly water-soluble, low-molecular-weight albumins and globulins, accounting for 18–29% on a dry matter basis (DMW), and are characterized by a non-compact structure. Its mineral profile shows relatively high concentrations of potassium (25–37 mg/100 g), copper (0.06–0.17 mg/100 g), and manganese (0.04–0.11 mg/100 g). The carbohydrate fraction consists primarily of monosaccharides such as D-galactose, D-glucose, and L-arabinose, with smaller amounts of D-xylose and D-fructose. The elevated saponin content (4–40 mg/g DMW), plant-derived glycosides with surface-active and foaming abilities, contributes to aquafaba functional properties (Sahin et al., 2024). Owing to its compositional characteristics, aquafaba serves as an effective plant-based emulsifier capable of forming stable emulsions with prolonged storage stability (Raikos et al., 2020; Włodarczyk et al., 2022).

Another aspect of improving the sensory and physicochemical properties of mayonnaises and mayonnaise-based sauces is the use of blends instead of single oils. Firstly, such an approach makes it possible to optimise the fatty acid composition of mayonnaise. To create blends, oils from both traditional and niche crops are used, such as dill, flax, black cumin, arugula, mustard, milk thistle, pumpkin, and sesame, among others (Sharma et al., 2019; Starikov et al., 2023). The incorporation of niche crop oils into blends extends the shelf life of the final product due to the presence of essential compounds such as polyphenols, quinones, flavonoids, alkaloids, and tocopherols, which exhibit antioxidant and antimicrobial activities. The antioxidant activity of many of these compounds exceeds that of synthetic antioxidants. For instance, the antioxidant effect of thymoquinone, which is contained in black cumin oil, ranges from 2.1% to 3.5%, is higher than that of butylated hydroxyanisole (E320) and butylated hydroxytoluene (E321) (Asfaw, 2023; Kmiecik et al., 2025). Secondly, oil blending allows fine-tuning of the physicochemical and sensory characteristics of mayonnaise. Different oils possess unique flavor profiles and aromas. Thus, the use of blends not only improves nutritional value but also enables the development of innovative products with unique textures and flavor qualities that meet the demands of the modern market.

Encapsulation of oils and their blends into nanoemulsions is a promising strategy both for enhancing oxidative stability (Gürbüz et al., 2018), and for improving the bioavailability of individual components (Bajerski et al., 2016).

The aim of this study was to develop low-fat mayonnaise emulsions based on blends of sunflower, hempseed, and black cumin oils, using aquafaba from canned white beans as the primary emulsifier. The focus was placed on investigating the structural, rheological, and sensory characteristics of the obtained emulsions, which are crucial for understanding their stability and consumer properties.

Materials and methods

Materials

The ingredients used in the formulation of the mayonnaise samples were obtained from the Ukrainian retail network and met the established food quality criteria, confirming their compliance with safety standards for food production.

Mayonnaise samples preparation

The mayonnaise samples were prepared according to the method (Sachko et al., 2023). The formulation of all sauces (per 100 g of product) included the following ingredients: mustard powder – 1.0 g, cream powder (46%) – 1.0 g, sodium chloride – 1.0 g, sucrose – 1.5 g, sodium bicarbonate – 0.05 g, pectin – 0.04 g, xanthan gum – 0.03 g, carboxymethylcellulose – 0.03 g, food-grade vinegar – 8.0 g, concentrated lactic acid – 0.3 g, water – 41.15 g, aquafaba obtained from canned white beans (Veres trademark) – 15.0 g, and vegetable oil – 30.0 g. In the control mayonnaise sample (M0), the oil phase was composed exclusively of refined sunflower oil. Samples M1 and M2 were formulated using blends of sunflower, hempseed, and black cumin oils at ratios of 70:25:5 and 45:50:5, respectively. These formulations provided ω-6:ω-3 fatty acid ratios of 10:1 and 5:1. The composition of the oil blends was calculated according to the method described by Matveeva et al. (2013). The addition of 5% black cumin oil was intended to enhance lipid oxidative stability while maintaining acceptable organoleptic properties of the final product (Khormizi et al., 2019).

Methods

Sensory analysis

The sensory properties of the mayonnaise samples were assessed using a descriptive profiling method on a 0–10 scale, where 0 represented the absence or minimal expression of a characteristic and 10 indicated its maximum intensity. The evaluated attributes included aroma, appearance, texture (consistency), color, taste, aftertaste, pungency (spiciness), and acidity. Each sause was evaluated individually to enable a quantitative description of consumer-relevant characteristics. The evaluations were carried out in a specialized sensory laboratory in accordance with ISO 8589:2007. Mayonnaise samples were presented in numbered disposable containers in random order. The final score for each attribute was calculated as the arithmetic mean of the values assigned by all panel members.

Emulsion sedimentation stability

The sedimentation stability of the emulsion was evaluated using an accelerated centrifugation method. For this purpose, 10 mL sauce of the mayonnaise sample was transfered into centrifuge tubes and subjected to a centrifugal force at 5000 rpm for 5 minutes. After centrifugation, the height of the separated liquid laysers (aqueous and oil fractions) was measured. The sedimentation stability coefficient (S, %) was then calculated using the following equation:

$$S = [(V_e - V_f)/V_e] \cdot 100\%,$$

where V_e is the volume of the undisturbed (or undestroyed) emulsion, and V_f is the volume of the separated aqueous or oil phase.

Determination of particle size distribution

The particle size distribution of the emulsion was measured using a laser diffraction instrument (PCA 1190, Anton Paar, Austria). The emulsion was dilutted with distilled water at a 1:100 ratio at room temperature (~20 °C). Measurements were performed under two conditions: without ultrasonic treatment and with ultrasonic treatment, which was applied for 5 minutes while continuously stirring the sample. Based on the measurements, the following parameters were calculated:

Surface-weighted (Sauter) mean diameter D[3,2]:

$$D[3,2] = \sum_i^N n_i d_i^3 / \sum i^N n_i d_i^2$$

Volume-weighted (De Brouckere) mean diameter D[4,3]:

$$D[4,3] = \sum_i^N n_i d_i^4 / \sum i^N n_i d_i^3$$

Polydispersity of the emulsions (Span):

$$Span = (D_{90} - D_{10})/D_{50},$$

where n_i is the number of droplets with diameter d_i, and D_{10}, D_{50}, and D_{90} are the percentile values indicating the size below which 10%, 50%, or 90% of all particles are found.

The flocculation index was calculated according to the formula:

$$FI= D[4,3])/(D[3,2].$$

Microphotographic analysis

For microphotographic analysis, the mayonnaise samples were diluted with distilled water at a 1:10 ratio. Microphotographs were captured using a Micromed microscope equipped with an integrated Pixelink 1K camera and a 60× objective lens.

Evaluation of rheological properties of emulsions

The rheological properties of the mayonnaise samples were investigated using a rotational viscometer Visco QC 300R (Anton Paar, Austria) at 20 °C. The dependence of shear stress on shear rate in the range of 0.1–100 s was measured using a coaxial cylinder system (CC12) in accordance with ISO 3219-2:2021 and DIN 53019-1:2008. To determine the yield stress (τ_y), measurements were conducted at a shear rate of 5 s^{-1} using a vane-type spindle, V75.

To describe the rheological behavior of the sauces, the experimental data were approximated using the Ostwald–de Waele (power-law) model, which is commonly applied for food products:

$$\tau = K \cdot \gamma^{n-1},$$

where K is the consistency coefficient, which indicates the system viscosity; *n* is the flow behaviour index,

and the Casson equation

$$\tau^{½} = (\tau_c^{½} \cdot \gamma^{½})/(\chi+\gamma^{½}) + \eta_c^{½} \cdot \gamma^{½},$$

where χ is the compactness coefficient of the structure, $\tau_c^{½}$ is the yield stress according to the Casson model, and $\eta_c½$ is the plastic viscosity.

The thixotropic behavior of the mayonnaise samples was evaluated using a three-interval thixotropy test (3ITT). The first and third intervals were conducted at a shear rate of 20 s^{-1}, while the second interval was conducted at 200 s^{-1}, with each stage lasting 5 minutes. The Thixotropic Breakdown Coefficient was calculated according to the following equation:

$$T_b = (\eta_1 - \eta_2)/\eta_1,$$

where η_1 is the initial viscosity, and η_2 is the viscosity of the system at the end of the second measurement interval.

The Structural Recovery Coefficient (SRC, %) was calculated using the following equation:

$$SRC = [(\eta_3 - \eta_2)/(\eta_1 - \eta_2)] \cdot 100\%,$$

where η_1 is the maximum viscosity value reached at the end of the first stage; η_2 is the lowest viscosity value recorded at the end of the second stage; and η_3 is the viscosity value measured at the end of the third stage.

The total surface area of the fat phase in the emulsion system (S_{fat}) was be calculated by the following formula:

$$S_{fat}=6V_{fat}/(D[3,2]),$$

where V_{fat} is a fat phase content.

Statistical analysis

A minimum of three parallel measurements was performed for each parameter. The quality of data fitting was assessed using the coefficient of determination (R^2) and the standard error of estimate (σ_{est}). The final results are presented with their corresponding standard deviation (SD). Statistical analysis was conducted using one-way Analysis of Variance (ANOVA), and differences in mean values relative to the control sauce were evaluated using Dunnett's post hoc test (significant differences are indicated by a–b indices next to the reported values).

Results and discussion

Sensory evaluation of mayonnaise samples

The sensory characteristics of mayonnaise samples are a critical determinant of consumer appeal and market success. Therefore, a detailed evaluation of these parameters is a key step in developing and ensuring the quality of novel mayonnaise formulations. The components of the oil blends used, particularly hempseed and black cumin oils, have distinctive aftertastes, requiring careful adjustment of their proportions to achieve a balanced flavour profile without excessive intensity that could be perceived negatively by consumers. Figure 1 presents comprehensive data, including the surface appearance of the mayonnaise samples in consumer packaging, their texture upon extrusion (dispensing from the tube), and the sensory attribute profilogram.

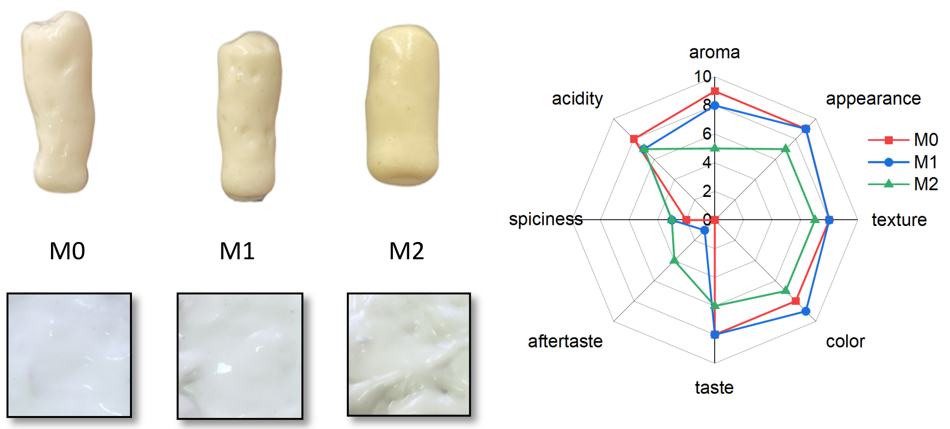


Figure 1. Appearance and sensory profile (profilogram) of the investigated mayonnaise samples:
M0, control with sunflower oil; M1 and M2 with blends of sunflower, hempseed, and black cumin oils at ratios of 70:25:5 and 45:50:5, respectively

Mayonnaise samples M0 and M1 were characterised by a larger curve area compared with M2, indicating more favourable sensory properties. At the same time, the perceived "acidity level" in samples M1 and M2, prepared with blended oils, was lower than in the control sample M0. The pH values of all mayonnaise samples were similar, ranging from 3.58 to 3.64. This effect can be attributed to the distinctive spicy notes of hempseed and black cumin oils, which may partially mask the acidic taste.

These findings are consistent with the literature (Helikh et al., 2021; Kryskova et al., 2023), which reports that the incorporation of hempseed oil up to 50% does not negatively affect sensory characteristics, whereas higher levels (above 75%) significantly reduce product quality. Although aquafaba from canned white beans contains a relatively low protein content (0.36 g/100 g), it was sufficient to form a stable emulsion. Legume-derived aquafaba is known for its high emulsifying activity index (EAI); for example, the EAI of chickpea aquafaba is nearly eight times higher than that of egg yolk (13.75 m^2/g versus 1.78 m^2/g, respectively) (Włodarczyk et al., 2022). The sedimentation stability coefficient measured on the second day after preparation was 98%. This high stability can be attributed to the presence of heat-soluble hydrophilic proteins in legume aquafaba, which exhibit high thermal stability and strong emulsifying capacity, as well as to the sufficient content of saponins that help prevent emulsion destabilisation (Schmidt et al., 2023). All studied mayonnaises exhibited 99% sedimentation stability after 24 hours. Furthermore, no visual changes or signs of separation were detected in the emulsions after one month of storage.

The stability of food emulsions largely depends on droplet size: the smaller the droplets, the greater the kinetic stability of the emulsion against physical destabilisation phenomena such as creaming, coalescence, and Ostwald ripening. According to Kim et al. (2020), relative stability of food emulsions is typically achieved when the droplet size is below 500 nm. The size of the dispersed phase is strongly influenced by the type and content of oil (Urbánková et al., 2019), the nature and concentration of the emulsifier (Gürbüz et al., 2018), and the technological conditions used for emulsion preparation (Mikulcová et al., 2017).

Gürbüz et al. (2018) reported the formation of coarse rapeseed oil emulsions (5%) stabilised with quinoa and amaranth proteins, exhibiting droplet sizes below 1 μm in all samples. Comparable values (~0.3 μm) were observed for black cumin oil emulsions (5–7.5%) stabilised with sucrose palmitate (Jufri et al., 2022) and for hempseed oil emulsions stabilised with the non-ionic surfactants Span 85/Tween 85 (Mikulcová et al., 2017). The simplest method for confirming flocculation phenomena in such systems is optical microscopy (Fig. 2).

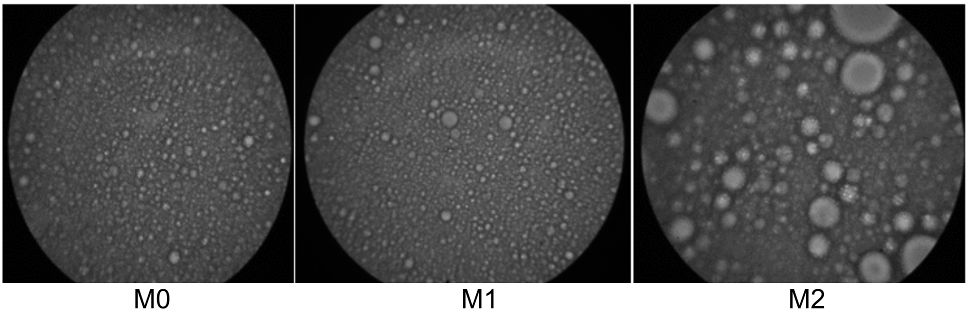


Figure 2. Microphotographs of emulsion samples M0, M1, and M2:
M0, control with sunflower oil; M1 and M2 with blends of sunflower, hempseed, and black cumin oils at ratios of 70:25:5 and 45:50:5, respectively

Mayonnaise samples M0 and M1 predominantly consisted of particles of comparable size, although some larger droplets were also visible. In contrast, analysis of the magnified image of sample M2 revealed a noticeably broader particle size distribution, ranging from very fine to considerably larger droplets. A distinct localisation of smaller droplets on the surfaces of larger ones was observed, indicating particle flocculation, which is reflected in the increased D[4,3] value.

To assess the effect of flocculation, the droplet size of the emulsion phase was measured both before and after ultrasonic treatment of the mayonnaise samples (Table 1), while the distribution curves themselves are shown in Fig. 3.

Table 1

Characteristics of particle size distribution in mayonnaise samples

Sauce	Measurement regime	Volume weighted distribution, µm						D[3,2], µm
		D10	D50	D90	D[4,3]	Span	FI	
M0	wUS	1.88	5.33	10.61	6.20	1.64	1.63	3.79
	US	1.74	4.49	8.11	5.04	1.46	1.47	3.42
M1	wUS	1.90	5.56	11.53	6.57	1.73	1.72	3.81
	US	1.72	4.38	8.09	5.01	1.45	1.50	3.35
M2	wUS	1.88	5.11	17.81	8.58	3.11	3.47	2.47
	US	1.53	3.41	7.62	4.36	1.78	1.88	2.31

Note: wUS – without ultrasonic treatment; US – with ultrasonic treatment.

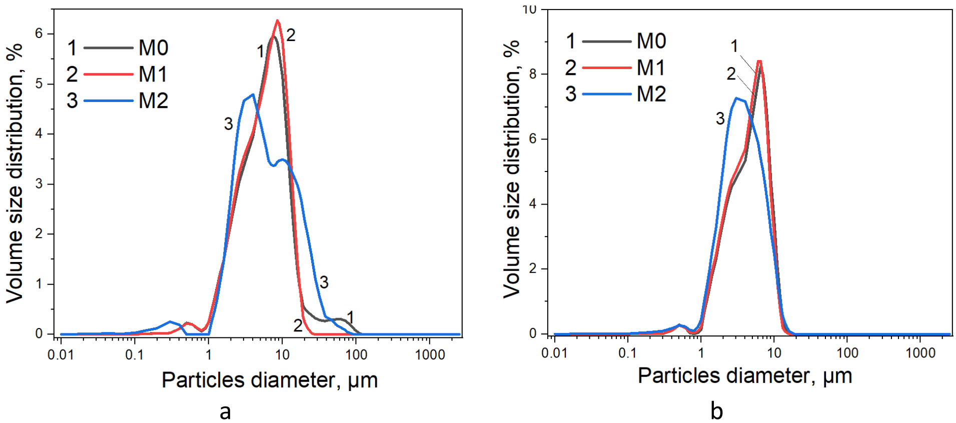


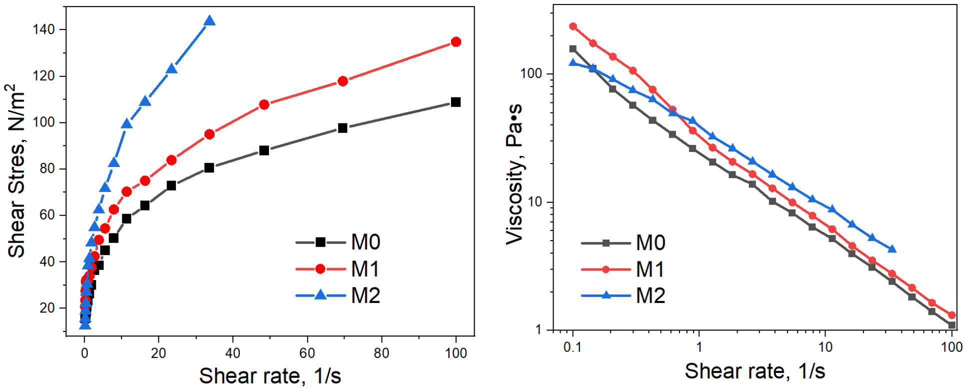
Figure 3. Volume-based particle size distribution of mayonnaise emulsions on the first day after preparation:
(a) without sonication, (b) with sonication

Analysis of the resulting curves showed that sonication caused a shift in the droplet size distribution toward smaller diameters in all samples, while in sample M2 the distribution changed from bimodal to monomodal. These observations confirm the occurrence of flocculation phenomena in the studied systems. To evaluate the effect of flocculation, droplet size measurements of the emulsion phase were conducted both with and without ultrasonic treatment (Fig. 3). Analysis of the resulting curves showed that sonication shifted the droplet size distribution toward smaller diameters in all samples, while in sample M2 the distribution changed from bimodal to monomodal. These results confirm the presence of flocculation processes in the studied systems. For samples M0 and M1, the D[4,3] values were similar (~5.01–5.04 µm). In contrast, sample M2 exhibited a lower D[4,3] value (4.36 µm) after ultrasonication, reflecting the disruption of floccules. The flocculation index (Table 1) increased in the order M0 < M1 < M2, irrespective of treatment. Sample M2, containing the oil blend at a 45:50:5 ratio, exhibited the highest degree of flocculation.

Under wUS conditions, Span values were similar for samples M0 and M1 (1.61 and 1.63, respectively) but nearly twice as high for sample M2. This indicates a higher degree of homogenization and a more uniform droplet size distribution in M0 and M1. The substantial increase in Span and flocculation index (FI) for M2 may be attributed both to the higher α-linolenic acid content in the oil phase and the presence of floccules. Włodarczyk et al. (2022) reported that replacing camelina oil (α-linolenic acid ~37%) with flaxseed oil (α-linolenic acid ~52%) increased mayonnaise droplet size from 45.28 µm to 56.75 µm. Similarly, Urbánková et al. (2019) observed flocculation when emulsifier concentrations were insufficient.

The total surface area of the fat phase in the emulsion system (S_{fat}) is a key factor in emulsion stability, as a larger surface area requires a greater amount of emulsifier to achieve stabilization. In the studied systems, M0 and M1 exhibited the same fat phase surface area, 4.7×10^5 m²/m³, whereas sample M2 showed a significantly higher value of 7.3×10^5 m²/m³. This confirms the importance of considering the type of oil when determining the emulsifier quantity needed to form a stable dispersed system. A similar effect was reported by Urbánková et al. (2019), where the particle size of an emulsion containing black cumin and tamanu oils, emulsified with sodium caseinate, increased from 2.2 to 7.8 µm as the tamanu oil content rose from 5% to 30%.

Viscosity is an important characteristic of emulsions, directly influenced by the size of the dispersed phase. The experimentally obtained flow curves indicate that the studied systems exhibit typical pseudoplastic (shear-thinning) behavior (Fig. 4a).



a b

Figure 4. Rheological behavior of the emulsion samples: flow curves for the emulsion samples (a) and changes in emulsion viscosity under the shear rate (b)

Shear thinning behavior was observed for all emulsions, with viscosity decreasing as the shear rate increased from 0.1 to 100.0 s^{-1}. The flow curves of sauces M0 and M1 were nearly identical, reflecting the similar properties of their dispersed phases due to the high sunflower oil content in the blends. In contrast, the flow curve of sample M2 indicated that higher shear stress was required to disrupt its internal structure. Across the entire measurement range, sauce M0 exhibited the lowest viscosity (Fig. 4b), while sauce M2, containing the highest proportion of hempseed oil, showed the highest initial viscosity at a shear rate of 0.1 s^{-1}. At shear rates above 1.1 s^{-1}, the curves for M1 and M2 crossed, indicating that sauce M2 displayed greater resistance to deformation at higher shear rates.

The obtained flow curves were analysed using the Ostwald–de Waele and Casson models. The results indicate that both models provided a satisfactory description of the shear stress–shear rate relationship for all samples (Table 2).

Table 2

Yield stress values and coefficients of the rheological model equations

Sauce	Ostwald-de Waele model			Experimental data
	K	***N***	***R^2***	***τ_y***
M0	26.35±0.48	0.312±0.005	0.996	76.5[a]
M1	38.41±0.94	0.367±0.008	0.995	106.3[b]
M2	35.48±0.91	0.276±0.007	0.990	81.7[a]
Casson's model				
Sauce	***χ***	***η_c***	***τ_c***	***R^2***
M0	0.372±0.046[a]	0.08±0.06[b]	72.2±9.8[a]	0.996
M1	0.311±0.022[a]	0.15±0.08[b]	81.9±5.9[a]	0.999
M2	0.168±0.023[b]	1.93±0.38[a]	40.4±4.1[b]	0.998

Note: Different letters in the column indicate a statistical difference of the mean relative to the control sauce, according to Dunnett's post hoc test at a significance level of $p<0.05$.

This is supported by the high correlation coefficients and low root mean square deviations between the experimental data and values calculated from the non-linear regression equations. For the Ostwald–de Waele model, the obtained n values <1 confirm the pseudoplastic behavior of the emulsions. Lower n values correspond to a greater decrease in viscosity with increasing shear rate, as observed for the highly flocculated sauce M2. The experimentally determined yield stress (τ_y), representing the point at which the elastic structure of the emulsion begins to break down, is presented in Table 2. The lower yield stress of sample M2 compared with M1 is consistent with Casson model calculations, indicating reduced structural strength. These results are in agreement with the microstructural observations (Fig. 2), which show that sample M2 is more flocculated, leading to a looser internal structure.

According to the Casson equation, the dynamic yield stress (τ_c) for samples M0 and M1 exhibits statistically identical values, which are higher than that of sample M2. This indicates the greater structuredness of emulsions M0 and M1, which contributes to increased viscoelasticity. This fact is corroborated by the correlation between the structure compactness coefficient (χ) and the emulsion droplet size distribution parameters (Fig. 5).

A reduction in the droplet size and polydispersity of the dispersed phase promotes the formation of a more compact and stable emulsion structure, as evidenced by an increase in the structure compactness coefficient (Gubsky et al., 2023). Shear flow, which is commonly applied in rheological experiments on food emulsions and emulsion-based products, induces both reversible and irreversible structural changes that are often time-dependent. These changes are reflected rheologically as variations in viscosity. The recovery of the structure to its initial state after the cessation of shear reflects thixotropic behavior.

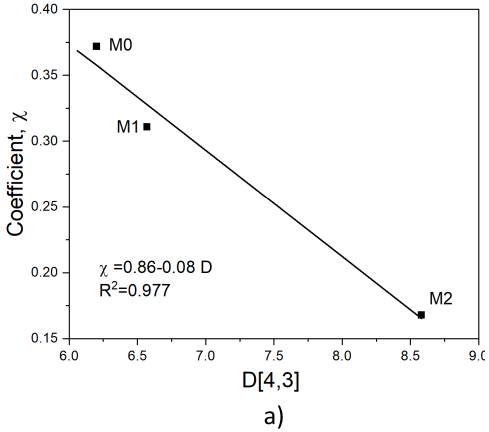


Figure 5. Dependence of the structure compactness coefficient (χ) on D[4,3] (a) and polydispersity factor Span (b) for emulsion samples

Thixotropic behavior is more accurately characterized using a dedicated step-wise three-interval test rather than relying solely on flow curve hysteresis (3ITT) (Fig. 6).

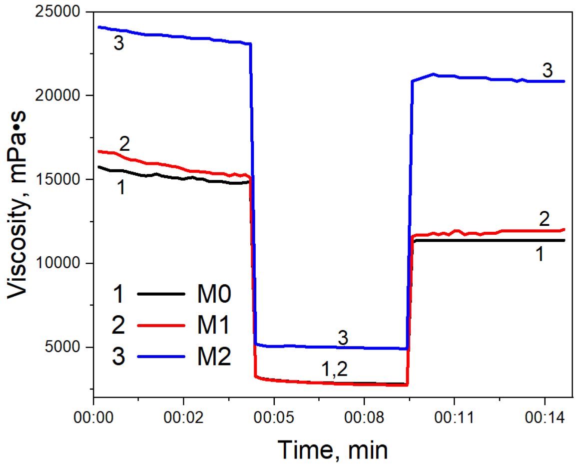


Figure 6. Results of the three-interval thixotropic test (3ITT) for emulsions M0, M1, and M2

The step-wise three-interval test (3ITT) consists of three phases: the first interval simulates the resting state of the emulsion, the second applies an abrupt structural breakdown, and the third monitors the time-dependent recovery of structural parameters. In this study, viscosity was used as the controlled parameter. The thixotropic breakdown coefficients and the structure recovery coefficient, calculated from the 3ITT curves, are presented in Table 3.

Table 3

Thixotropic behavior of the emulsion samples

Sauce	Thixotropic Breakdown coefficient (T_b)	Coefficient of structural recovery (CSR), %
M0	0.189^{a}	71.1
M1	0.180^{a}	73.1
M2	0.212^{b}	87.3

Note: Different letters in the column indicate a statistical difference of the mean relative to the control sauce, according to Dunnett's post hoc test at a significance level of $p<0.05$.

For all investigated emulsions, a sharp drop in viscosity was observed during the second interval, corresponding to structural breakdown and a change in consistency. The relatively high breakdown coefficient (T_b) for emulsion M2 indicates that its structure is easily disrupted under external stress. At the same time, emulsion M2 exhibited the highest structure recovery coefficient (CSR), whereas this coefficient was considerably lower for samples M0 and M1. These results indicate that, despite its susceptibility to breakdown, emulsion M2 recovers its structure relatively quickly. This behavior can be attributed to the larger dispersed phase particle size and higher flocculation tendency of emulsion M2 compared with M0 and M1. These characteristics facilitate the rapid reformation of the spatial structure once the external stress is removed. The combination of easy structural breakdown and quick recovery represents highly desirable properties for mayonnaise-type sauces.

Conclusions

A stable emulsion formulation with a balanced fatty acid composition was developed using blends of sunflower, hempseed, and black cumin oils (30% fat phase) and canned bean aquafaba as a natural emulsifier. Such samples have reduced nutritional value and, due to the use of vegetable proteins, may be of interest for vegan nutrition. The study confirmed the high emulsifying efficiency of aquafaba, attributed to its thermostable hydrophilic proteins and saponins, which promote stable emulsion formation. Ultrasound treatment further reduced droplet size, disrupted flocs, and produced a more homogeneous dispersed system. However, increasing the proportion of hempseed oil broadened the droplet size distribution from 1.64 to 3.11. Mayonnaises containing more than 50% hempseed oil exhibited pronounced flocculation, observable by optical microscopy, and a higher total fat phase surface area (7.3×10^5 m^2/m^3), indicating that higher emulsifier concentrations are required to maintain stability in such formulations.

Rheological analysis showed that all mayonnaise samples exhibited pseudoplastic behavior, regardless of oil phase composition. Formulations with over 50% hempseed oil displayed higher viscosity at low shear rates, lower yield stress, and lower sensory scores. The most favorable balance of sensory and physicochemical properties was observed was achieved with the 70:25:5 sunflower:hempseed: black cumin oil blend, which combined sufficient thixotropy with a high structure recovery coefficient, making it suitable for mayonnaise production requiring easy breakdown and rapid structure regeneration.

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