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Physicochemical and structural properties of vegan mayonnaise prepared with peanut sprout oil and aquafaba

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A R T I C L E I N F O

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A B S T R A C T

Peanut sprout oil (PSO), rich in unsaturated fatty acids, and aquafaba, a chickpea-derived emulsifier, were used to formulate vegan mayonnaise. This study examined the impact of different aquafaba-to-oil ratios (PA1: 33:60, PA2: 28:65, PA3: 23:70) on the physicochemical, microstructural, and sensory properties of the formulations. As aquafaba content decreased, pH values, centrifugal and thermal stabilities were reduced. Emulsions with less aquafaba had larger oil droplets, leading to weaker emulsion stability and texture. Among the samples, PA1 exhibited the most desirable characteristics, including firmness and physical stability comparable to conventional egg-based mayonnaise. Microstructural analysis confirmed that smaller and more uniform droplets contributed to improved stability. PA1 formulations had the highest oxidative stability, and the absence of egg yolk did not increase lipid oxidation. Sensory evaluation revealed that PA1 received the highest scores for overall acceptability. These findings support the use of PSO and aquafaba as effective ingredients in vegan mayonnaise formulations.

1. Introduction

The increasing consumer demand for healthier foods, along with the prevalence of veganism due to growing environmental concerns, has led the food industry to explore replacing animal-derived ingredients with plant-based alternatives (Huang et al., 2022). Mayonnaise is traditionally classified as a semisolid emulsion composed of oil, egg, vinegar, and spices. It forms a stable colloidal system, where emulsified oil droplets with a spherical morphology are dispersed within a homogeneous aqueous phase. (Laca et al., 2010). Egg yolk, a key emulsifying agent in conventional mayonnaise, is highly valued for its ability to form stable emulsions and contribute to the desired texture (Depree & Savage, 2001). However, eggs contain high cholesterol levels that can lead to cardiovascular diseases and are a common allergen, particularly among infants and young children (Lin et al., 2017). Additionally, the use of raw eggs in mayonnaise presents a risk of contamination with *Salmonella* spp., posing a food safety concern (Smittle, 2000). This transition toward egg-free formulations is driven by both health and sustainability concerns, aligning with consumer preferences for natural, allergen-free, and ethically produced products. Furthermore, eliminating egg yolk from mayonnaise simplifies production processes, as pasteurization is no longer necessary (Raikos et al., 2020). However, achieving a stable structure in vegan mayonnaise that can withstand prolonged storage without coalescence or flocculation remains a challenge (Yildirim et al., 2016).

Plant proteins derived from pulses and legumes, recognized for their diverse functional properties such as water holding, fat-binding, solubility, gelling, foaming, and emulsification, offer a promising substitute for animal-derived proteins in various food applications (Buhl et al., 2019). Armaforte et al. (2021) reported that different legumin proteins (faba bean, chickpea, and yellow split lentils) produced stable mayonnaise samples with sensory properties comparable to egg yolks mayonnaise. Ozcan et al. (2023) observed that egg yolk replacement with aquafaba protein increased the density of mayonnaise, while texture parameters decreased. Specifically, aquafaba is a viscous liquid formed during cooking chickpeas or found in canned chickpea products (Raikos et al., 2020). Aquafaba contains protein, water-soluble/insoluble carbohydrates (oligosaccharide, starch, cellulose, hemicellulose, and lignin), polysaccharide-protein complexes, saponins, and phenolic compounds (He et al., 2021) and possesses functional properties including emulsibility, gelation, foamability, and thickening attributed to its composition. Research indicates that aquafaba is a valuable ingredient with desirable functional properties, making it suitable for use in various formulations to replace eggs and milk in vegan products

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(Serventi et al., 2018; Stantiall et al., 2018). Aquafaba has been widely adopted in various industries, including bakery, dressings, ice cream, cheese, and dairy products (Włodarczyk et al., 2022). Ali and el Said (2020) and Raikos et al. (2020) assessed aquafaba's potential as an egg replacer for vegetarian mayonnaise formulation production, reporting its successful use in substituting eggs in mayonnaise formulas containing standard amounts of oil.

Peanut sprout oil (PSO), derived from sprouted peanuts, is a functional oil rich in unsaturated fatty acids—approximately 37 % oleic acid (C18:1) and 35 % linoleic acid (C18:2) (Jeong et al., 2023). Additionally, PSO contains bioactive compounds such as resveratrol, which has been associated with various health benefits, including cardiovascular protection and anti-inflammatory properties (Gambini et al., 2015; Jin et al., 2008). Its natural antioxidant content enhances oxidative stability, making it a valuable ingredient in food formulations. Despite its nutritional and functional advantages, PSO has not been widely incorporated into processed foods, presenting an opportunity for innovation in vegan mayonnaise development.

Therefore, this study aimed to explore the potential of PSO in vegan mayonnaise by formulating samples with varying PSO-to-aquafaba ratios and evaluatilng their microstructure, stability, texture, and overall consumer acceptability.

2. Materials and methods

2.1. Chemical and reagents

Peanut sprout oil (PSO) was purchased from Reborn Food & Clinic Co. (Hwaseong, Korea). Aquafaba (Fratelli Longobardi S.R.L, SA, Italy), white sugar (CJ Co., Seoul, Korea), salt (CJ Co., Seoul, Korea), lemon extract (Natalie's Orchid Island Juice, FL, USA), corn oil, and eggs were obtained from a local market. *Trans*-Resveratrol was purchased from Sigma-Aldrich Co., Ltd. (St. Louis, MO, USA). Other reagent-grade chemicals were acquired from Daejung Chemical Co. (Seoul, Korea).

2.2. Characterization of aquafaba

2.2.1. pH

The pH of aquafaba and mayonnaise was measured at 25 °C using a pH meter (SI Analytics GmbH D-55122, Mainz, Germany) with the method described by Kumar et al. (2021).

2.2.2. Water holding capacity (WHC) and oil holding capacity (OHC)

Water holding capacity and oil holding capacity of aquafaba were determined according to the methods outlined in Alsalman et al. (2020). 1 g of freeze-dried aquafaba was mixed with 10 mL distilled water or oil, vortexed for 30 s, and allowed to stand at 25 °C for 1 h. The samples were then centrifuged at 4000 rpm for 30 min, and the supernatant was removed. The difference in weight between the empty tube and the one after centrifugation was recorded as WHC and OHC.

2.2.3. Moisture content

Moisture content was determined following the method described by Tasie and Gebreyes (2020). 2 g of aquafaba samples (WS) were transferred to dried and weighed dishes (W1). The samples were placed in a dry oven and dried overnight at 105 °C. Subsequently, the dried samples were removed from the oven, cooled in a desiccator at room temperature, and reweighed (W2).

$$\text{Moisture content (\%)} = \frac{(W_1 - W_2)}{W_S} \times 100$$

2.2.4. Protein content

Protein content was determined using the Kjeldahl method. The distilled sample was titrated with 0.1 N NaOH until the first appearance of the pink color.

$$\text{Crude protein content (\%)} = \frac{((b - a) \times 0.0014 \times 5.71)}{W} \times 100$$

here, a is the volume of NaOH used for the aquafaba sample (mL), b is the volume of NaOH used for the blank (mL), 0.0014 is the 0.1 N NaOH factor, and 5.71 is the conversion factor for protein from % nitrogen.

2.3. Characterization of vegan mayonnaise containing PSO

2.3.1. Mayonnaise preparation

Table 1 displays the formulations for egg-free mayonnaises containing PSO and the samples were named by the ratio of PSO and aquafaba: corn oil 65 g + egg 28 g (CE), PSO 65 g + egg 28 g (PE), PSO 60 g + aquafaba 33 g (PA1), PSO 65 g + aquafaba 28 g (PA2), PSO 70 g + aquafaba 23 g (PA3). Briefly, vegan mayonnaise samples were prepared using a blender (BL642KR, Nutri Ninja Duo Auto-iQ, SharkNinja, Shenzhen, China). Egg or aquafaba, along with salt (1.2 g), sugar (1.8 g), and xanthan gum (0.5 g) was mixed at high speed (16,000 rpm) for 2 min. Oil was then gradually added while blending continued for an additional 6 min. Finally, lemon extract (4 g) was incorporated into the mixture. The prepared mayonnaise samples were stored in sealed containers at 4 °C.

2.3.2. Analysis of trans-resveratrol content of vegan mayonnaise

The sample preparation was conducted following the method described by Li et al. (2022). The trans-resveratrol content in the oil of mayonnaise was analyzed using ultra-high performance liquid chromatography-tandem mass spectrometry (LCMS-8060NX, Shimadzu, Japan). The column used was ZORBAX SB-C18 (2.1 × 50 mm, 1.8 μm, Agilent Technologies, Inc., CA, USA). The mobile phase comprised solvents, with (A) filtered sterile water containing 0.1 % formic acid and (B) HPLC-grade acetonitrile. The flow rate was set at 0.6 mL/min, and trans-resveratrol served as the standard for both qualification and quantification purposes. Sample pretreatment involved using oil extracted from mayonnaise. 5 g sample and 1.2 mL of 80 % ethanol were mixed using a vortex, and the mixture was then centrifuged at 4000 rpm for 10 min. The supernatant was collected three times and filtered through a 0.22 μm organic filter membrane (Jet Biofil, Guangzhou, China).

2.3.3. Centrifugal stability of vegan mayonnaise

The centrifugal stability of mayonnaise was determined following the method described by Wang et al. (2022). 3 g of mayonnaise sample (W_0) were heated in a water bath at 60 °C for 60 min. Subsequently, the sample was centrifuged at 8000 rpm for 10 min. Following centrifugation, the supernatant was carefully removed, and the remaining mayonnaise was weighed (W_1). The emulsion stability was described as follow:

$$\text{Emulsion stability (\%)} = \frac{W_1}{W_0} \times 100$$

2.3.4. Thermal stability of vegan mayonnaise

The thermal stability of mayonnaise was conducted according to the

Table 1
PSO-mayonnaise formulation.

%	CE	PE	PA1	PA2	PA3
Corn oil	65	–	–	–	–
Peanut sprout oil	–	65	60	65	70
Egg	28	28	–	–	–
Aquafaba	–	–	33	28	23
Xanthan gum	–	–	0.5	0.5	0.5
Salt	1.2	1.2	1.2	1.2	1.2
Sugar	1.8	1.8	1.8	1.8	1.8
Lemon extract	4	4	4	4	4

method described by Wang et al. (2022). 3 g of mayonnaise sample (W_0) were placed in an oven at 80 °C for 30 min. The sample was then centrifuged at 8000 rpm for 10 min. Finally, the supernatant was removed, and the remaining mayonnaise was weighed (W_1).

$$\text{Thermal stability }(\%) = \frac{W_1}{W_0} \times 100$$

2.3.5. Color properties of vegan mayonnaise

The color parameters of mayonnaise samples, including light-dark value (L^*), red-green value (a^*), and yellow-blue value (b^*), were measured by a colorimeter (CR400, Konica Minolta Sensing, Inc., Osaka, Japan). Based on these values, the whiteness index and yellowness index were calculated according to the method described by Tiwari et al. (2022). The total color difference (ΔE) of samples was also determined using the following equation.

$$\text{Whiteness index} = 100 - \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2}$$

$$\text{Yellowness index} = \frac{142.86 \times b^*}{L^*}$$

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

2.3.6. Microstructure of vegan mayonnaise

The mayonnaise structure was observed using a microscope (BX53 microscope, Olympus Corporation, MA, USA) equipped with a magnification of 40× at 25 °C. A drop of prediluted mayonnaise sample (1:2, sample: water ratio) was deposited onto a slide and covered with a cover glass.

2.3.7. Particle size of vegan mayonnaise

The particle size of mayonnaise samples was determined according to the method by Primacella et al. (2019). Particle size distribution was measured using a particle size analyzer (ELSZ-2000ZS, Otsuka Electronics, Osaka, Japan). A refractive index of 1.4000 was used for the dispersed oil phase, composed of sprout peanut oil and chickpea-derived aquafaba. This value was selected based on preliminary optical assessments and literature values of plant-based oils and natural emulsifiers. The scattering intensity during measurement was 26,771 cps. For sample preparation, 10 g of each mayonnaise sample was diluted with 20 mL of 0.2 % (*w/v*) sodium dodecyl sulfate solution solution to minimize droplet coalescence. The mixture was gently vortexed until complete dispersion was achieved. D10, D50, and D90 represent the diameter of particles inside the range of 10 %, 50 %, and 90 %, respectively, of the cumulative sample particles.

2.3.8. Textural properties of vegan mayonnaise

The texture properties of mayonnaise were assessed using a texture analyzer (TA-XT plus, Stable Micro Systems, Surrey, UK) equipped with a spreadability fixture and a 5 kg load cell at room temperature. The mayonnaise samples were filled into a 45 mm dia acrylic female 90 °C cone and smoothed off at the top. The male cone was inserted at a speed of 3 mm/s until it reached 2 mm above the bottom of the female cone. The maximum force (spreadability) and the work of shear were then recorded.

2.3.9. Rheological properties of vegan mayonnaise

The rheological properties of PSO-based mayonnaise samples were measured using a rheometer (DHR-10, TA Instruments, New Castle, DE, USA) equipped with a 40 mm parallel plate geometry at 25 °C. Flow curves were obtained by measuring the shear stress as a function of shear rate ranging from 0.1 to 100 s^{-1}. Apparent viscosity values were recorded throughout the shear rate range. The flow behavior was evaluated by fitting the shear stress–shear rate data to the Herschel–Bulkley model using nonlinear regression analysis.

$$\tau = \tau_0 + K\gamma^{\dot{n}}$$

where τ is the shear stress (Pa), τ_0 is the yield stress (Pa), k is the consistency index (Pa·s^n), γ is the shear rate (s^{-1}), and n is the flow behavior index (dimensionless).

2.3.10. Peroxide value of vegan mayonnaise

The peroxide value (POV) was determined according to the method by Nepote et al. (2006) on the lipid of mayonnaise. The mayonnaise was stored under accelerated conditions (60 °C) for 28 days, as previously described in similar studies evaluating lipid oxidation in emulsified food systems (Jeong et al., 2023; Baştürk & Yavaş, 2024). And the oil of the mayonnaise was extracted using the fat extraction method described above before measurement. In brief, 1 g of the oil phase of the mayonnaise was dissolved in 25 mL of a mixture of chloroform: acetic acid (1:2, *v/v*) at 450 rpm for 3 min. 1 mL of potassium iodide solution was added, and the mixture was stirred for 10 s, then the sample was allowed to react in the dark for 10 min. Afterward, 30 mL of distilled water was added and stirred at 450 rpm for 5 min. Finally, 1 mL of starch solution (1 %) was added, and the sample was titrated with sodium thiosulfate (0.01 N). The POV was expressed as milliequivalents of peroxide per kilogram of the sample (meq O_2/kg).

2.3.11. Sensory characteristics of vegan mayonnaise

Participants in the sensory evaluation have given their consent to take part in the sensory assessment and use their information. 30 untrained panelists (16 women and 14 men aged 21–29) participated in the sensory evaluation. Sensory evaluation of mayonnaise samples was conducted using a nine-point hedonic scale (1-dislike very much and 9-like very much) to assess visual appearance, color, flavor, creaminess, graininess, taste, and overall acceptability. The samples were presented at room temperature in white plastic dishes with teaspoons. The tasting sessions involved a randomized serving order, and the samples were blind-coded with random three-digit numbers for unbiased evaluation. Water was served to rinse the palate in between samples.

2.4. Statistical analysis

All experiments were conducted in triplicate, and the values are expressed as means ± deviation. Statistical analysis was performed using SPSS software (IBM SPSS Statistics 27, IBM Corp., Armonk, NY, USA). The *t*-test and Duncan's multiple-range test were used for mean comparisons. Significance among the samples was determined at a confidence level of 95 %.

3. Result and discussion

3.1. Characterization of aquafaba

The pH, WHC, OHC, moisture content, and protein content were analyzed to explore the physicochemical characteristics of aquafaba used in this study. The pH of aquafaba affected its foaming capacity and the emulsifying stability index; this was primarily influenced by the protein concentration in the solution. The aquafaba used in this study exhibited a pH of 6.05 (Table 2). Investigations conducted on aquafaba

Table 2
Physicochemical properties of aquafaba.

	Aquafaba
pH	6.05 ± 0.00
Water holding capacity (g/g)	3.39 ± 0.18
Oil holding capacity (g/g)	3.60 ± 0.01
Moisture content (%)	95.34 ± 0.96
Protein content (%)	1.37 ± 0.04

adjusted from pH 2 to 8 showed that aquafaba at pH 6 had high protein solubility, emulsifying activity, and stability (Lafarga et al., 2019; Tontul et al., 2018). The WHC and OHC of aquafaba are associated with the concentration of lignin, cellulose, and hemicellulose complexes, which exhibit hydrophobic properties. The abundance of hydrophilic groups induces interactions, leading to high WHC. WHC influences the quality characteristics (color, texture, and sensory properties) of finished food products. On the other hand, OHC affects emulsification properties, shelf-life, and consumer acceptability, including texture, flavor retention, and mouthfeel (Mustafa & Reaney, 2020). WHC and OHC of freeze-dried powder of aquafaba are shown in Table 2. Two main factors affecting WHC and OHC include various soaking and cooking conditions and differences in aquafaba composition (Alsalman et al., 2020; He et al., 2021). As the cooking time progresses, protein denaturation occurs, resulting in hydrophobic molecular regions becoming exposed and thus changing its WHC and OHC. In this study, the WHC and OHC of canned chickpeas were 3.39 and 3.60, respectively. A study by Alsalman et al. (2020) reported that WHC (1.4 to 2.7 g/g) and OHC (0.9 to 3.5 g/g) values ranged in a wide range due to differences in cooking times and chickpea-water ratios. Moisture content and protein content of aquafaba were 95.34 % and 1.37 %. Considering the previous study (Mustafa et al., 2018; Raikos et al., 2020) which indicated that fat was not detected, the fat content was not analyzed in this study. Deep Singh et al. (2008) reported that the peptide mass fingerprinting and electrophoresis analyses of aquafaba showed aquafaba proteins primarily consisted of low molecular weight species (<25 kDa), likely albumins, well-known for foaming properties. Thus, it is likely that the combination of low molecular weight protein and carbohydrates confers the remarkable foaming and emulsifying capacity observed in aquafaba. According to Mustafa et al. (2018), aquafaba contains heat-stable proteins, which not only contribute to its high thermal stability but also impart unique functional properties. Therefore, aquafaba demonstrates the ability to function over a broad temperature range, presenting possibilities for novel applications.

3.2. Characterization of vegan mayonnaise containing PSO

The visual appearance of vegan mayonnaise is shown in Fig. 1. When comparing the CE and PE samples, differences in mayonnaise formation were observed depending on the type of oil used, even though the same egg emulsifier was used. Also, with an increase in aquafaba content, a more cohesive form of mayonnaise was formed.

3.2.1. pH of vegan mayonnaise containing PSO

Traditional mayonnaise typically results in an acidic emulsion with a long shelf-life, often lasting up to 6 months when stored under refrigerated temperatures (Raikos et al., 2020). In this study, there were no significant differences in pH between the two egg-based mayonnaises; however, among the aquafaba-based samples, a higher aquafaba content was associated with a higher pH. Vegan mayonnaise samples formulated with different ratios of PSO and aquafaba exhilbilted lower pH values, ranging from 4.24 to 4.39, compared with egg mayonnaise samples (pH 4.96) (Table 3). Similar findings were reported by Raikos et al. (2020), who observed pH values ranging from 3.45 to 3.67 in vegan mayonnaise formulated with aquafaba, and by He et al. (2021), who also found that aquafaba-based mayonnaise had lower pH values compared to egg yolk-based formulations. These findings support the trends observed in this study. It is well known that aquafaba has a naturally neutral to slightly alkaline pH (approximately 6.0–7.5), which differs from the typically acidic nature of traditional egg yolk-based mayonnaise. Therefore, pH adjustment using food-grade acids was necessary to lower the pH and ensure microbiological safety, oxidative stability, and sensory acceptability. Notably, mayonnaise samples prepared with aquafaba and xanthan gum showed significantly lower pH values than those made with eggs, indicating the potential for improved shelf-life. However, it has also been reported that reducing pH to enhance emulsion stability may negatively affect the foaming capacity and protein functionality of aquafaba (Mustafa et al., 2018). These factors should be carefully considered in future formulation optimization.

3.2.2. Trans-resveratrol content of vegan mayonnaise

The resveratrol content of mayonnaise was measured by the UPLC-MS/MS method (Table 3). In this study, the identification of resveratrol was confirmed by a commercial standard of trans-resveratrol; PSO and PO gave off an identical retention time and fragment ion at m/z values of 227, 185, and 143. Peak identification was determined by the

Table 3
Physicochemical properties of PSO-mayonnaise samples.

	pH	Trans-resveratrol (μg/L)	Emulsion stability (%)	Thermal stability (%)
CE	4.96 ± 0.00 a	0.01 ± 0.00 b	99.67 ± 0.00 a	99.67 ± 0.00 a
PE	4.96 ± 0.00 a	0.26 ± 0.01 a	98.34 ± 0.32 b	98.22 ± 0.85 b
PA1	4.39 ± 0.00 b	0.25 ± 0.01 a	99.56 ± 0.51 a	98.90 ± 0.83 ab
PA2	4.28 ± 0.00 c	0.26 ± 0.00 a	82.02 ± 0.57 c	95.23 ± 0.68 c
PA3	4.24 ± 0.00 d	0.26 ± 0.00 a	62.98 ± 0.22 d	67.95 ± 0.41 d

(CE: corn oil 65 g + egg 28 g, PE: peanut sprout oil 65 g + egg 28 g, PA1: peanut sprout oil 60 g + aquafaba 33 g, PA2: peanut sprout oil 65 g + aquafaba 28 g, PA3: peanut sprout oil 70 g + aquafaba 23 g, (a–e) Means with different letters in the same column differ significantly at $p < 0.05$)

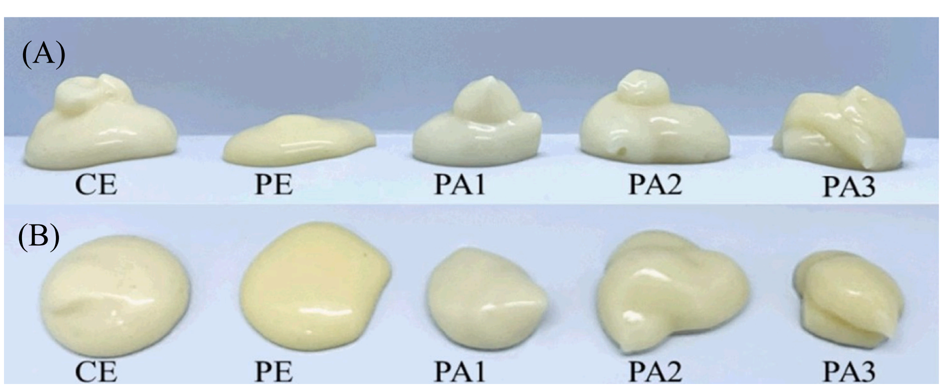


Fig. 1. Side (A) and top (B) images of PSO-mayonnaise samples.
(CE: corn oil 65 g + egg 28 g, PE: peanut sprout oil 65 g + egg 28 g, PA1: peanut sprout oil 60 g + aquafaba 33 g, PA2: peanut sprout oil 65 g + aquafaba 28 g, PA3: peanut sprout oil 70 g + aquafaba 23 g)

mass spectra and fragmentation patterns, comparing their m/z charge to reference compounds and published data. A significantly higher amount of resveratrol was observed in mayonnaise prepared from PSO. The resveratrol content of CE mayonnaise was only 0.01 μg/L, and the resveratrol content of PSO mayonnaises ranged from 0.25 to 0.26 μg/L, approximately 25 times higher than that in CE.

3.2.3. Centrifugal and thermal stability

The centrifugal stability and thermal stability of vegan mayonnaise samples were investigated (shown in Table 3). No significant changes in centrifugal and thermal stability were observed between PA1 and CE. The lowest values for centrifugal and thermal stability of the sample were obtained in PA3, and the lower the aqaquafaba content, the lower the centrifugal and thermal stability. Centrifugal and thermal stability are important quality characteristics of mayonnaise and are affected by the size and uniformity of the oil droplets (Drozłowska et al., 2020). In mayonnaise, oil droplets are closely packed and strongly interact due to the high fat content, where small and uniform oil droplets contribute positively to the stability of the emulsion. Compared to aquafaba, the emulsifying molecules in egg yolk are much smaller. Generally, emulsifiers with smaller particle sizes produce smaller oil droplets, leading to enhanced stability within an emulsion system. In egg-yolk-based mayonnaise, lecithin (particularly phospholipids) acts as a surfactant to facilitate emulsion formation, whereas in vegan mayonnaise, aquafaba, composed of proteins and polysaccharides, likely enhances colloidal stability to achieve a stable emulsion. However, further research is needed to elucidate the precise emulsion mechanisms underlying these processes.

3.2.4. Color properties of vegan mayonnaise

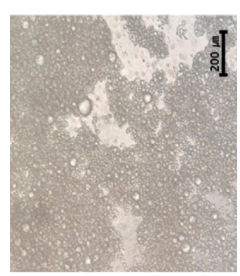
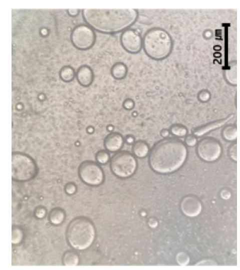
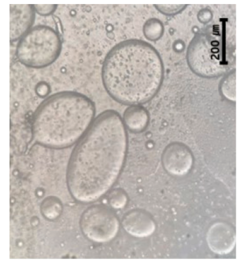
Table 4 presents L^*, a^*, b^*, white index (WI), and yellow index (YI). Color is a crucial parameter influencing the overall appearance and acceptability of mayonnaise. L^* represents the ability of mayonnaise to reflect and scatter light, having a significant impact on consumer perception (Ozcan et al., 2023). Generally, in mayonnaise, larger oil droplet sizes result in lower lightness (L^*) values, even when the same additives are used. This study also demonstrates this trend, as the L^* values for PA1, PA2, and PA3 decreased to 81.72, 79.93, and 76.52, respectively, with increasing oil droplet sizes (as shown in Table 5). On the other hand, a previous study by Flamminii et al. (2020) found that the typical yellow color of mayonnaise originates from egg yolk, similar to our study. CE and PE showed the highest b^* values at 35.57 and 43.56. Additionally, PA1, PA2, and PA3 samples without added egg had low b^* values of 14.28, 15.18, and 17.54. The addition of egg lowered the WI of

Table 4
Color properties of PSO-mayonnaise samples.

	L^*	a^*	b^*	Whiteness index	Yellowness index	ΔE
CE	81.18 ± 0.01 ^{b}	−3.02 ± 0.01 ^{b}	20.21 ± 0.01 ^{b}	72.22 ± 0.01 ^{c}	35.57 ± 0.01 ^{b}	–
PE	79.23 ± 0.04^{d}	−3.61 ± 0.01 ^{d}	24.16 ± 0.03 ^{a}	67.94 ± 0.05 ^{e}	43.56 ± 0.08 ^{a}	4.44 ± 0.01 ^{d}
PA1	81.72 ± 0.01 ^{a}	−2.74 ± 0.01 ^{a}	14.28 ± 0.01 ^{e}	76.64 ± 0.01 ^{a}	24.96 ± 0.02 ^{e}	7.16 ± 0.01 ^{c}
PA2	79.93 ± 0.04 ^{c}	−2.76 ± 0.02 ^{a}	15.18 ± 0.02 ^{d}	74.69 ± 0.03 ^{b}	27.14 ± 0.03 ^{d}	9.04 ± 0.02^{b}
PA3	76.52 ± 0.02 ^{e}	−3.23 ± 0.02 ^{c}	17.54 ± 0.02 ^{c}	70.51 ± 0.03 ^{d}	32.75 ± 0.04 ^{c}	10.23 ± 0.02 ^{a}

(CE: corn oil 65 g + egg 28 g, PE: peanut sprout oil 65 g + egg 28 g, PA1: peanut sprout oil 60 g + aquafaba 33 g, PA2: peanut sprout oil 65 g + aquafaba 28 g, PA3: peanut sprout oil 70 g + aquafaba 23 g, (a–e) Means with different letters in the same column differ significantly at $p < 0.05$)

Table 5
Microstructure, particle size, texture and rheological parameters of PSO-mayonnaise samples.

	CE	PE	PA1	PA2	PA3
Microstructure images					
Average diameter (μm)	16.90 ± 1.52 ^{d}	17.98 ± 1.40 ^{d}	183.27 ± 13.79 ^{c}	262.45 ± 16.69 ^{b}	514.75 ± 35.85 ^{a}
D10	5.46 ± 1.57 ^{d}	6.64 ± 1.74 ^{d}	159.91 ± 21.99 ^{c}	189.89 ± 11.38 ^{b}	340.35 ± 29.29 ^{a}
D50	118.70 ± 11.37 ^{d}	124.46 ± 1.71^{d}	204.38 ± 30.38 ^{c}	243.17 ± 15.51 ^{b}	387.49 ± 20.94 ^{a}
D90	334.56 ± 36.77 ^{bc}	396.27 ± 58.53 ^{b}	261.79 ± 40.53 ^{c}	312.40 ± 21.40^{c}	526.05 ± 48.52 ^{a}
Firmness (N)	1.36 ± 0.11 ^{a}	0.60 ± 0.07^{d}	1.19 ± 0.24 ^{ab}	1.06 ± 0.02 ^{bc}	0.84 ± 0.15 ^{c}
Work of shear (N•s)	1.18 ± 0.10 ^{a}	0.50 ± 0.07 ^{c}	1.11 ± 0.23 ^{a}	1.00 ± 0.03 ^{ab}	0.79 ± 0.17 ^{b}
τ_0 (Pa)	38.56 ± 1.93 ^{b}	7.27 ± 0.09 ^{e}	44.93 ± 4.93 ^{a}	29.49 ± 0.81 ^{c}	15.39 ± 1.52 ^{d}
K (Pa•s^{n})	19.09 ± 0.87 ^{a}	4.27 ± 0.17 ^{d}	15.03 ± 2.87 ^{b}	6.95 ± 0.24 ^{c}	4.97 ± 0.01 ^{cd}
n	0.35 ± 0.03 ^{c}	0.52 ± 0.03 ^{a}	0.44 ± 0.04 ^{b}	0.51 ± 0.00 ^{a}	0.54 ± 0.00 ^{a}
R^2	0.97	0.99	0.99	0.99	0.98

(CE: corn oil 65 g + egg 28 g, PE: peanut sprout oil 65 g + egg 28 g, PA1: peanut sprout oil 60 g + aquafaba 33 g, PA2: peanut sprout oil 65 g + aquafaba 28 g, PA3: peanut sprout oil 70 g + aquafaba 23 g, (a–e) Means with different letters in the same row differ significantly at $p < 0.05$)

mayonnaise; PE prepared with PSO and egg had the lowest WI, and PA1 had the highest WI. This observation indicated that aquafaba might enhance the whiteness index of mayonnaise. Despite using the same emulsifier, distinct color variations were observed depending on the type of plant-based oil. Moreover, a significant increase in the total color difference (ΔE) was noted with higher oil content, with PA3 exhibiting the highest ΔE value.

3.2.5. Microstructure and particle size of vegan mayonnaise

The microstructure and particle size analysis of mayonnaise samples were conducted to investigate the droplet size of mayonnaise samples (Table 5). These characteristics play a pivotal role in understanding the texture, viscoelastic properties, and overall quality and acceptability of the product. Several factors, including the type and concentration of emulsifiers, viscosity of the aqueous phase, oil content, and droplet size, influence the microstructure of mayonnaise (Laca et al., 2010). Microstructural analysis revealed that all mayonnaises consisted of finely dispersed, spherical oil droplets within the aqueous medium. CE exhibited the densest structure, attributed to the use of egg yolk as an emulsifying agent. The use of egg yolk in mayonnaise contributes to its high solubility in the typical pH range of food emulsions, facilitating efficient absorption at the oil-water interface (Le Denmat et al., 2000). In contrast, PA1, PA2, and PA3 displayed larger interspace voids and oil droplet sizes compared to CE and PE, which was consistent with the result of particle size measurements. The average diameter of PA1, PA2, and PA3 was approximately 10 to 30 times larger than CE and PE. This notable difference can be attributed to the primary composition of aquafaba, rich in carbohydrates and proteins. Polysaccharides within aquafaba possess remarkable thickening properties due to their hydrophilicity and high molecular weight. These properties contribute to a higher viscosity of the aqueous phase and restrict the formation of fine, evenly distributed droplets in vegan mayonnaise analogs. Moreover, the high concentration and molecular weight of insoluble polysaccharides in aquafaba result in the formation of a thick gel layer around the oil droplets, further enlarging their size (Yildirim et al., 2016). The microstructural changes observed in mayonnaise samples underscore the impact of ingredient composition on the physical properties of the product, which in turn influencs texture and overall consumer perception. Furthemore, to understand the emulsion mechanism formed by PSO and aquafaba, further research by using a SEM or confocal microscopy is required to investigate colloidal interactions and emulsifying properties between oil droplets and emulsifiers.

3.2.6. Texture of vegan mayonnaise

Texture parameters in vegan mayonnaise are also presented in Table 5. Firmness is an important parameter of maximum force measured by equipment, influencing both sensory characteristics and the applicability of mayonnaise. In mayonnaise, the substantial contact surface area between oil droplets leads to significant friction forces that resist the free flow of the emulsion in a shear field. This phenomenon contributes to an increase in viscosity. Generally, a reduction in oil droplet diameter results in a larger contact surface area between droplets, leading to increased firmness (Liu et al., 2007). Among the mayonnaises using the same oil (PSO), the firmness was significantly decreased with decreasing aquafaba contents or increasing particle size. The firmness of the PA1 prepared with the highest aquafaba content was 1.19 N, it was most similar to the CE. The oil droplet diameter of the samples can reflect the texture analysis parameters. On the other hand, the CE had the highest firmness of 1.36 N, while PE had the lowest firmness of 0.60 N. The firmness value was different due to the different types of oil although the same emulsifier was used between CE and PE. As investigated in Table 5, the particle size (average diameter) was not observed significant difference depending on the type of oil, but the firmness characteristics were different, which is presumed to be due to the different fatty acid compositions of the oils used. In addition, further research about this needs to be conducted.

3.2.7. Rheological properties of vegan mayonnaise

The effect of different ratios of aquafaba to PSO on the apparent viscosity of vegan mayonnaise samples is shown in Fig. 2. All samples exhibited a decrease in apparent viscosity with increasing shear rate, indicating pronounced shear-thinning behavior and non-Newtonian flow characteristic. The viscosity results showed a consistent trend with the previously presented texture data. Although the same emulsifier (egg yolk) was used, the viscosity of mayonnaise varied depending on the oil type. In particular, mayonnaise containing PSO with aquafaba and xanthan gum exhibited higher viscosity compared to egg yolk-based PSO mayonnaise. At shear rate of 10 s^{-1}, the viscosities of all samples were reduced to lower than 10 Pa•s, indicating that the microstructure of the network was substantially disrupted and could not be reformed within the short time of shear application (Taslikh et al., 2022). The apparent viscosity curves are usually described well by the Hurschel-Bulkley model. The calculated K and n values are given in Table 5. For all samples, $n < 1$, indicates the pseudoplastic nature of the mayonnaise (Pei et al., 2023). The K values of the CE were higher than those of the aquafaba based-samples, and these differences were statistically significant ($p < 0.05$). A lower value of K indicates a less strong and time-stable structure of the aquafaba-based samples compared to the control. The increase in K value and decrease in n value with increasing aquafaba ratio suggested that aquafaba molecules and xanthan gum bridged droplet to droplet, enhancing the strength of the interactions between droplets. These results indicate the potential of PSO in producing mayonnaise with superior viscosity properties without the use of egg yolk.

3.2.8. Oxidative stability of vegan mayonnaise

The oxidative stability of the proposed mayonnaise formulations was evaluated to predict the shelf-life of the final product and to ensure its functionality and safety during storage. Peroxide value (POV) was used to quantify the level of primary oxidation products, including peroxides and hydroperoxides. A lower POV indicates a slower rate of oxidation, reflecting greater oxidative stability of the oil. Changes in POV during storage under accelerated conditions of oil extracted from mayonnaise are illustrated in Fig. 3. At day 0, no significant differences in POV were observed among the five mayonnaise samples. However, all samples showed a significant increase in POV over the storage period. Among them, the control (CE) exhibited the highest POV values, ranging from 6.50 to 50.67 meq O_2/kg of oil over 28 days. In contrast, the PE displayed significantly lower POV values compared to CE, despite both being prepared with the same amounts of oil and egg. This result suggests that although PSO is rich in polyunsaturated fatty acids, as reported in a previous study (Jeong et al., 2023), the presence of natural antioxidants in PSO effectively delays the formation of hydroperoxides, the primary oxidation products. While the resveratrol content of PSO was quantified in this study and may contribute to its antioxidant effects, it is acknowledged that a single compound does not represent the overall antioxidant profile. Other bioactive components, such as tocopherols, phytosterols, and polyphenols, may also influence oxidative stability. Therefore, future research should include analysis of fatty acid composition, antioxidant compounds, and their activity to further elucidate the mechanisms underlying the oxidative stability of PSO-containing products. Moreover, the samples PE and PA2, which differed only in the type of emulsifier used, exhibited comparable POV values, suggesting that replacing egg with aquafaba did not negatively affect the oxidative stability of the mayonnaise. Additionally, a correlation between oil content and POV was observed among the aquafaba-based samples; higher oil content was associated with higher POV values. After 28 days of storage, the final POVs of CE, PE, PA1, PA2, and PA3 were 50.67, 40.33, 39.33, 42.24, and 45.33 meq O_2/kg oil, respectively. While this study primarily focused on POV as an indicator of primary oxidation, future studies should incorporate the evaluation of acid value and secondary oxidation products (e.g., TBARS) to provide a more detailed and comprehensive assessment of the oxidative stability of mayonnaise

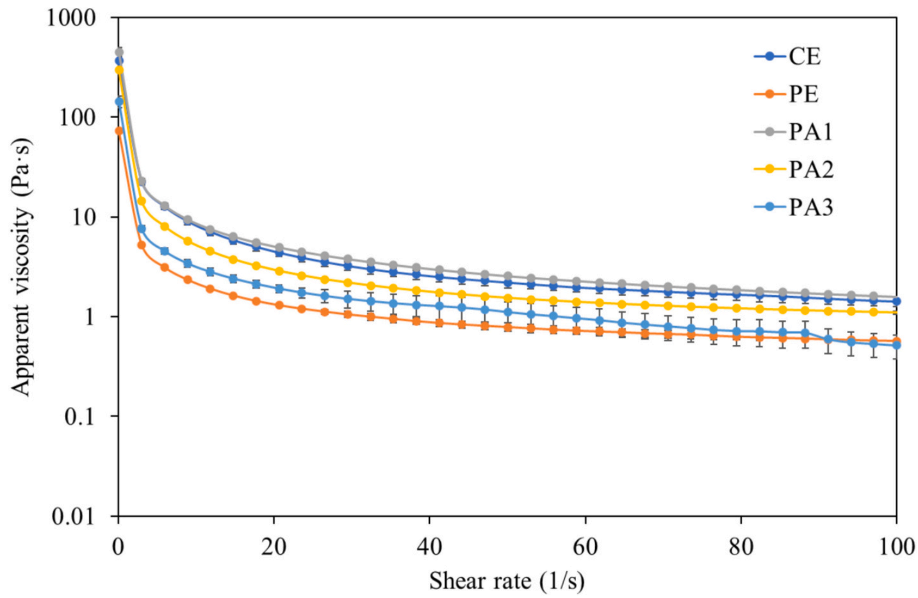


Fig. 2. The flow behaviors of vegan mayonnaises with different ratios of aquafaba to PSO (CE: corn oil 65 g + egg 28 g, PE: peanut sprout oil 65 g + egg 28 g, PA1: peanut sprout oil 60 g + aquafaba 33 g, PA2: peanut sprout oil 65 g + aquafaba 28 g, PA3: peanut sprout oil 70 g + aquafaba 23 g).

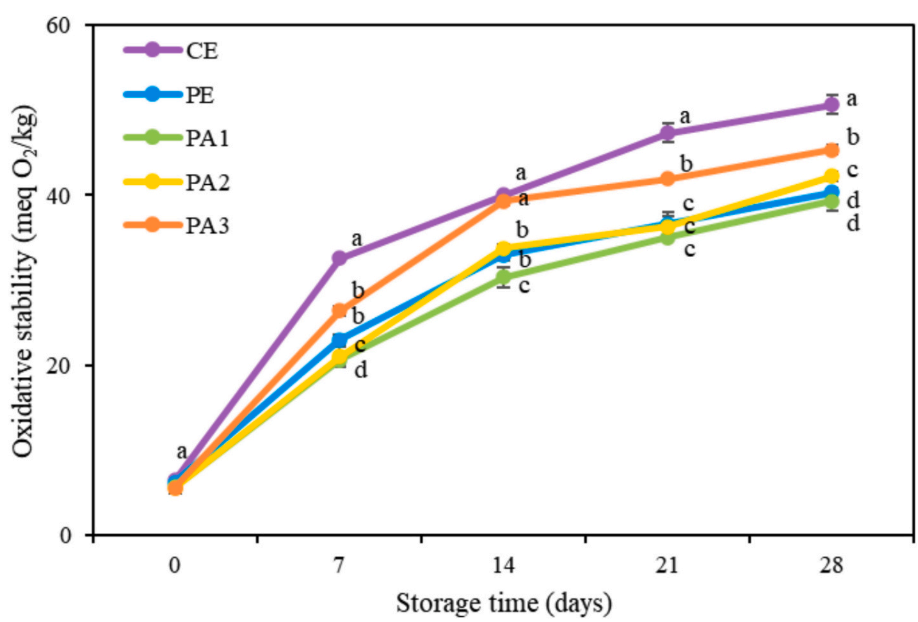


Fig. 3. The peroxide values of mayonnaises under accelerated storage condition.
(CE: corn oil 65 g + egg 28 g, PE: peanut sprout oil 65 g + egg 28 g, PA1: peanut sprout oil 60 g + aquafaba 33 g, PA2: peanut sprout oil 65 g + aquafaba 28 g, PA3: peanut sprout oil 70 g + aquafaba 23 g, (a–d) Different letters on the bars indicate that there is a significant difference at $p < 0.05$ among samples of the same storage time)

formulations containing PSO.

3.2.9. *Sensory characteristics of vegan mayonnaise*

Consumer decisions regarding mayonnaise are profoundly influenced by their preferences for food characteristics, such as appearance, flavor, color, texture, and taste (Jia et al., 2023). CE mayonnaise was excluded from sensory evaluation due to its perceived differences in its unique flavor using different oil types. Consequently, sensory evaluation was focused on visual appearance, flavor, color, creaminess, graininess, taste, and overall acceptability of four kinds of PSO mayonnaises. Fig. 4 reveals that mayonnaise samples prepared with aquafaba exhibited a more acceptable visual appearance compared to PE mayonnaise, predominantly influenced by their higher whiteness index (Table 5). The flavor and taste values were not significantly affected by both egg and aquafaba. However, the creaminess and graininess scores of PA3 were lower, attributed to its higher oil content. Conversely, PA1, with lower oil content, attained the highest creaminess and graininess scores. Overall acceptability scores were significantly higher when the oil content was lower and aquafaba was used instead of eggs. In conclusion, PA1 mayonnaise, endowed with superior visual appearance, color, creaminess, graininess, and overall acceptability, was deemed sensorially acceptable by consumers.

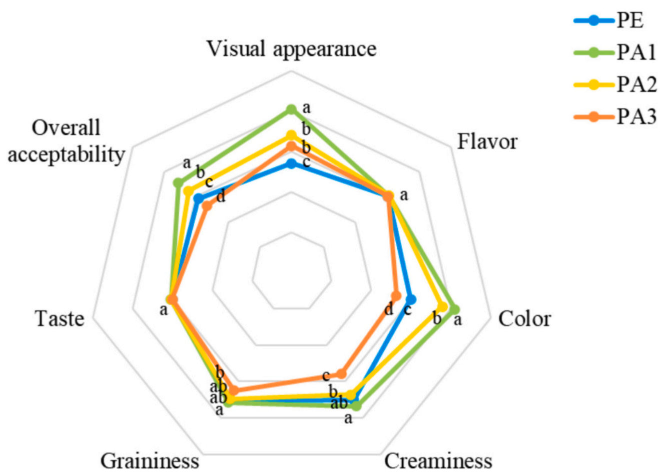


Fig. 4. Sensory evaluation of mayonnaise made with PSO and aquafaba. (CE: corn oil 65 g + egg 28 g, PE: peanut sprout oil 65 g + egg 28 g, PA1: peanut sprout oil 60 g + aquafaba 33 g, PA2: peanut sprout oil 65 g + aquafaba 28 g, PA3: peanut sprout oil 70 g + aquafaba 23 g, (a–d) Different letters on the bars indicate that there is a significant difference at $p < 0.05$)

4. Conclusions

This study demonstrated the successful formulation of a plant-based vegan mayonnaise using aquafaba and peanut sprout oil (PSO), both of which contributed to improving the physicochemical, oxidative, and sensory properties of the final product. The replacement of corn oil with PSO resulted in improved oxidative stability, as evidenced by lower peroxide values (POV) during accelerated storage compared to the control egg-based mayonnaise. Aquafaba effectively replaced egg yolk as a plant-based emulsifier, contributing to enhanced centrifugal and thermal stability, improved texture, and desirable sensory attributes. Particularly, the sample with the highest aquafaba content (PA1) showed comparable firmness and emulsion stability to egg-based mayonnaise while also exhibiting a more appealing whiteness index and microstructure. Particle size analysis confirmed that aquafaba's polysaccharide-protein matrix plays a role in the formation of stable emulsions, despite producing larger droplet sizes than those formed with egg yolk. Sensory evaluation revealed that mayonnaise samples with higher aquafaba content and lower oil levels achieved higher scores in overall acceptability. These results underscore the potential of aquafaba and PSO as synergistic plant-based ingredients for developing vegan mayonnaise with competitive quality compared to conventional products.

CRediT authorship contribution statement

Hyunjin Jeong: Visualization, Validation, Investigation, Formal analysis. **Imkyung Oh:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Investigation, Data curation, Conceptualization.

Ethics statement

Ethical approval for the involvement of human subjects in this study was granted by Sunchon National University Institutional Review Board (IRB number: 1040173–202,205-HR-008-02). The appropriate protocols for protecting the rights and privacy of all participants were utilized during the sensory evaluation, e.g., no coercion to participate, full disclosure of study requirements and risks, written or verbal consent of participants, no release of participant data without their knowledge, ability to withdraw from the study at any time.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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