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Enrichment with industrial waste whey protein and exotic fruit flours as an innovative and functional ingredient in the production of low-fat functional mayonnaise

Elif Cakir[1]*, Muhammed Sahin[1], Hatice Bekiroglu[2,3]*

[1]Department of Food Engineering, Faculty of Engineering, Istanbul Aydin University, Küçükçekmece, Istanbul, Türkiye; [2]Department of Food Engineering, Faculty of Agriculture, Sirnak University, Sirnak, Türkiye; [3]Department of Food Engineering, Chemical and Metallurgical Faculty, Yildiz Technical University, Istanbul, Türkiye

***Corresponding Authors:** Elif Cakir, Department of Food Engineering, Faculty of Engineering, Istanbul Aydin University, PO Box 38, 34295, Kücükcekmece, Istanbul, Türkiye. Email: elifcakir@aydin.edu.tr; Hatice Bekiroglu, Department of Food Engineering, Faculty of Agriculture, Sirnak University, Sirnak, Türkiye; Department of Food Engineering, Chemical and Metallurgical Faculty, Yildiz Technical University, Istanbul, Türkiye. Email: bkroglu@yildiz.edu.tr

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Abstract

The aim of this study was to produce low-fat mayonnaise using equal proportions of flours obtained from tropical fruits such as pineapple, coconut, and mango, and commercial waste whey protein powder as fat substitutes. The resulting mayonnaises were evaluated in terms of physical, chemical, nutritional, rheological, microbial, and sensory properties. Mayonnaises containing fruit flour had lower fat content (35.58%) and higher protein (7.28%) and dietary fiber content (22.38%) than control mayonnaises (CMYN). Fruit flours and whey protein powder significantly improved bioactive properties by increasing total phenolic content (TPC: 5.45–37.68 mg GAE/100 g) and antioxidant activity (DPPH: 19.22–27.95 mg TE/100 g; ABTS$^{\bullet+}$: 23.66–50.61 mg TE/100 g); MMYN (mango flour: whey protein powder) and PMYN (pineapple flour: whey protein powder) showed the strongest values. All samples exhibited pseudoplastic properties, while fruit flours increased the consistency. The highest viscosity and G" values were measured in CCMYN mayonnaise. pH was affected by fruit acidity, and microbial growth was slower in samples containing fruit flour. The addition of fruit flours increased the b* value. PMYN mayonnaise containing pineapple flour was liked as much as the control. Tropical fruit flours (especially pineapple flour) and whey protein powder have shown promising results in the production of reduced-fat mayonnaise with improved functional properties and sensory acceptance.

Keywords: coconut; mango; mayonnaise; pineapple; waste; whey protein

Introduction

Mayonnaise is a sauce containing 70%–80% fat and is traditionally an emulsion product consisting of a mixture of eggs, vinegar, oil, and spices (Depree & Savage, 2001; Raikos *et al.*, 2016; Zhao *et al.*, 2002). Increasing consumer preferences for nutritional and health-promoting benefits have led to the search for functional ingredients that can replace traditional fats in food products (Srikanth *et al.*, 2023). Mayonnaise is included among fatty products on the market because of the main component being derived from lipids. Low-fat mayonnaise is stated to contain 30–40% fat (Lee *et al.*, 2013). In contrast to traditional mayonnaise production, preparation needs to be based on reducing the oil phase and increasing the effective proportion of the water phase to obtain mayonnaise with less fat. Studies state that negativities will be experienced with the emulsion structure when the fat proportion of oil is reduced, and this situation may negatively impact consumer approval. As a result, there is a need for additives such as emulsifiers, thickeners, and stabilizers to increase the quality of mayonnaise. For low-fat mayonnaise, the emulsion stability may be increased by adding materials such as polysaccharides, gums, pectin, carrageenan, wheat protein, whey protein, and starches (Evanuarini & Susilo, 2020; Satriawan *et al.*, 2022). A significant portion of the waste produced by the dairy industry is whey, which, with its valuable components, can be a significant potential resource for the production of value-added products (Ganju & Gogate, 2017); its functional and nutritional properties make it effective in low-fat mayonnaise. Fruit flours, which may be obtained from by-products of fruit like from fruit, seeds, and peels, are accepted as a clean-label compound used as additive to enhance food properties (Ferreira *et al.*, 2015). Fruit flours may provide the opportunity to enhance mayonnaise formulations by increasing nutritional features with bioactive compounds such as carotenoids and phenolic acids, fiber and vitamins, and features that may develop the technological functions such as water-holding, thickening, and jellifying properties (Santos *et al.*, 2022; Vieira M. *et al.*, 2023). In addition, it is important to convert easily degrading fruits into stable products with longer life and to increase their potential for use in different products. Therefore, the objective of this research was to investigate the production of a low-fat mayonnaise formulated using the functional components of equal parts whey and tropical fruit flours instead of oil and to investigate the effects on the physicochemical properties, viscosity, emulsion stability, color, texture, and microbial and sensory features of the mayonnaise. In addition, the aim was to produce these mayonnaise samples without exceeding consumer perceptions about the habitual mayonnaise flavor.

Materials and Methods

Material

The raw materials for use in mayonnaise were obtained from local markets in İstanbul, including eggs (Anadolu Çiftliği, Çorum Yumurta Üretim Pazarlama A.Ş., Çorum, Türkiye), apple vinegar (CarrefourSA, Sabancı Ticaret Merkezi A.Ş., Türkiye), sunflower oil (Evin, Aves Enerji Yağ ve Gıda San. A.Ş, Türkiye), salt (Bim Birleşik Mağazalar A.Ş., Türkiye), and whey protein powder (70% protein) (Kalipso, Barbarossa Kimya Gıda San. Tic. Ltd. Şti, Türkiye). All reagents used in the study, including the DPPH and ABTS radicals, Folin–Ciocalteu reagent, and the solvents, were purchased from Sigma-Aldrich (St. Louis, MO, USA) and were of analytical grade.

Method

Preparation of fruit powders

The fruit powder samples to be used in the mayonnaise were provided by buying each fruit fresh from local markets. Fruits were sliced into thin strips and left to dry in an oven (Binder, ED24D Germany) at 55°C for 48 h. After drying, fruits were powdered in a grinder (Fakir, Aromatic, Germany) to obtain fruit flours.

Mayonnaise production

For mayonnaise production, the proportions of egg, sunflower oil, vinegar, salt, lemon juice, fruit powders, and whey protein powders were calculated, and production was completed. The raw materials and proportions used during production are shown in Table 1. For mayonnaise production, fruit flours (pineapple, coconut, and mango) and whey protein powder were used in 1:1 (w:w) ratio. After weighing the raw materials, the eggs were first placed in a beaker and blended with a hand blender (Arzum Monomix 900 W, Türkiye) at speed 1 for 10 s. Lemon, salt, sunflower oil, and apple cider vinegar were then added, and the blender was blended again for 15 s to obtain the final product. Production was completed for five different mayonnaise samples of CMYN (control mayonnaise without fruit flour and whey protein), WMYN (mayonnaise with whey powder), PMYN (mayonnaise with pineapple flour and whey powder), MMYN (mayonnaise with mango flour and whey powder), and CCMYN (mayonnaise with coconut flour and whey powder).

Analysis methods

% dry matter, % ash, and % protein

The dry matter amounts in mayonnaise samples were determined according to the gravimetric method in AOAC (2000). The ash content of mayonnaise samples was determined according to the AOAC international official analysis method using an ash oven (WiseTherm-Daihan FH-03, Korea). The sample was heated to 550°C for 12 h until organic matter was incinerated (AOAC, 2000). Protein content was determined using the Kjeldahl method (Jung *et al.*, 2003). Total dietary fiber content was determined with AOAC 985.29 (AOAC, 2005).

pH and titrable acidity (TA) analysis

The pH value was measured by dipping the probe of a pH meter (Mettler Toledo-S230 Seven Compact,

Table 1. Raw materials and their ratios used during production.

Raw materials	CMYN	WMYN	PMYN	CCMYN	MMYN
Egg	54.8 g	54.8 g	54.8 g	54.8 g	54.8 g
Apple vinegar	4.5 g	4.5 g	4.5 g	4.5 g	4.5 g
Lemon	2 g	2 g	2 g	2 g	2 g
Salt	1.2 g	1.2 g	1.2 g	1.2 g	1.2 g
Oil	120 g	110 g	100 g	100 g	100 g
Whey protein powder	–	10 g	10 g	10 g	10 g
Pineapple powder	–	–	10 g	–	–
Mango powder	–	–	–	–	10 g
Coconut powder	–	–	–	10 g	–

Switzerland) into the mayonnaise sample. The five different mayonnaise samples were titrated with 0.1 N NaOH solution by dilution to 1:10 (w:v) ratio with the aid of a sensitive scale (AND, GR-200, Japan).

Total oil amount

With the aim of determining the oil % in the five different mayonnaise samples and three different fruit powders, the Soxhlet extraction method was used. The 5 g samples were placed in the cartridges of the Soxhlet device extractor and extracted with 250 mL hexane. After extraction lasting 6 h in the Soxhlet extractor, the solvent was removed in the evaporator. The data were inserted into the following oil % equation, and the oil % amounts in the five different mayonnaise samples and three different fruit powders were identified (Sudjatinah, 2021).

$$\text{Oil (\%)} = \frac{M2 - M1}{M} \times 100$$

M1 is the weight of balloon brought to fixed weight (g), M2 is the total oil amount found in final weighing of balloon (g), and M is the sample weight (g).

Color analysis

The color measurements for the mayonnaise samples prepared with five different formulations were completed using a Hunter Lab Color CR-400 (Konica Minolta Sensing, Inc., Osaka, Japan) device. Color readings are given as L^* value [(0) black (100) white], a^* value [(+) red (–) green], and b^* value [(+) yellow (–) blue] (Wang *et al.*, 2022).

Extraction of mayonnaise samples

Mayonnaise samples were mixed at room temperature in a mixer for 20 min after adding methanol solution (70%) in 1:10 (w:v) ratio. The mixed mayonnaise samples were homogenized for 30 min in an ultrasonic water bath. Then, they were centrifuged at 4000 g for 30 min (NF 400R Bench Top Centrifuge, Belgium) to separate the oil phase, and the extract was passed through 0.45 μm filters (Filter-Lab, Spain) and stored at −20°C to determine bioactive properties (Gouvinhas *et al.*, 2014).

Determination of total phenolic content

Phenolic matter amounts were identified with the spectrophotometric approach using the Folin–Ciocalteu method. For this, to 0.1 mL of sample, 4.5 mL of distilled water, 0.1 mL of Folin–Ciocalteu agent (Merck, Germany), and 0.3 mL of 2% sodium carbonate (Na_2CO_3) were added in order. The mixture was left in a dark place at 25°C for 2 h. The absorbance of the mixture was measured with a spectrophotometer set to 760 nm (Optizen POP UV-Vis Spectrophotometer, Korea). Results are expressed as mg GAE/100 g (gallic acid equivalents) (Hamdani *et al.*, 2018; Singleton & Rossi, 1965).

Determination of antioxidant capacity (DPPH method)

Antioxidant activity examination used the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical inhibition activity test according to the method given by Brand William *et al.* (1995). From the mayonnaise extracts, 100 μL was taken, and the mixture was vortexed after adding 3.9 mL DPPH methanol solution. This was left in the dark at 25°C for 30 min for inhibition. At the end of the duration, the absorbance of the solution was measured with a spectrophotometer at 517 nm, and the DPPH radical inhibition percentage was determined according to the following equation. The experiment was repeated three times. Data were placed in the formula to determine the antioxidant capacity. Results are expressed as Trolox equivalents (TE) in mgTE /100 g. (Brand-Williams *et al.*, 1995).

Determination of antioxidant capacity ($ABTS^{•+}$ method)

$ABTS^{•+}$ stock solution was prepared by dissolving ABTS (Sigma, St. Louis, MO, USA) in 2.45 mmol/L potassium persulfate and leaving it for 15 h at room temperature in the dark while being stirred. At the end of the process, the stock solution was diluted with a certain amount of phosphate buffer, and the absorbance at 734 nm was set to 0.7 ± 0.05. Then, 30 μL of mayonnaise sample extract was mixed with 2 mL $ABTS^{•+}$ solution and incubated for 6 min.

Finally, the absorbance value was measured with a spectrophotometer at 734 nm (UV–vis 1800 Shimadzu, Japan), and results are stated as mgTE/100 g with the aid of a standard Trolox calibration curve (Miller & Rice-Evans, 1997).

Emulsion stability analysis

The five different mayonnaise samples that were produced were weighed in centrifuge tubes to 10 g with the aid of a sensitive scale. They were centrifuged at 4000 rpm for 35 min. The emulsion stability of the samples was calculated with the following emulsion equation (He *et al.*, 2021):

$$ES = \frac{F0 - F1}{F0} \times 100$$

ES is emulsion stability, F0 is the weighed sample (g), and F1 is the separated subphase (g).

Optical microscope observation

A light microscope (Zeiss, Germany) was used to examine the microstructure of the prepared mayonnaise samples. A drop of each sample was placed on a microscope slide and observed at 10X and 40X magnification. 40X image was obtained after staining with methylene blue (Merck,Germany) (Di Mattia et al., 2015).

Rheological measurements

Flow behavior rheological properties

All rheological analyses were completed using a stress and temperature-controlled rheometer (Anton Paar MCR 302, Graz, Austria). Rheological analyses were completed at 25°C with 0.5 mm gap. Flow behavior rheological properties were determined at shear rates in the range of 0.1–100 s^{-1}. The power law model was used for the data

$$\sigma = K\gamma n$$

σ is shear stress (Pa), K is the consistency index, γ is the shear rate (s^{-1}), and n is the flow behavior index.

Dynamical rheological properties

The amplitude sweep test was performed to determine the direct viscoelastic region. The oscillatory tests were completed in the 0.1–60 Hz frequency interval using the strain values (0.5%) for the linear viscoelastic region of each sample with shear module G' (storage module) and viscous component G'' (loss module) (mechanical spectra) module. Rheological parameters were calculated using the TA Instrument software program.

Total yeast and mold count

Mayonnaise samples were stored in glass jars at +4°C, and yeast and mold counts were performed at weeks 3, 4, 5, and 6. mayonnaise samples were serially diluted 10-fold. Yeast and mold counts were performed after incubation in Potato dextrose agar (PDA) agar medium at 28–30°C for 72 h.

Sensory analysis

With the aim of determining the sensory features and evaluating the consumability of the five different mayonnaise samples, sensory analysis was completed by a 40-person panelist group comprising Istanbul Aydin University students. Evaluation of mayonnaise samples was completed accompanied by potato fries. Mayonnaise samples were randomly named with three-digit codes and presented to panelists for analysis. Panelists evaluated the mayonnaise samples according to 13 parameters including sheen, color, mouthfeel, spoon consistency, smoothness, sourness, sweetness, flavor, oiliness, rancid flavor (bitterness), odor, aroma, flavor, and general approval. Rated according to a 6 point hedonic scale, samples were stated to be 1: very bad, 2: bad, 3: moderate, 4: neither good nor bad, 5: good, and 6: very good. Average scores of 4 points and above were evaluated as being liked. Figure 3 shows the sensory sample presented to panelists.

Statistical analysis

All experiments were performed in triplicate. All results were averaged and presented as mean ± standard deviation (SD). The data were subjected to one-way analysis of variance. The significant differences between samples were calculated using Tukey test ($p < 0.05$). SPSS for Windows version 16 (SPSS Inc., Chicago, IL, USA) was used for all data analysis.

Results and Discussion

Chemical and physical properties of mayonnaise

As a result of the analyses, five different mayonnaise samples (CMYN, WMYN, PMYN, MMYN, and CCMYN) had moisture %, ash %, protein%, pH, TA, oil %, emulsion stability, and color values identified. The physicochemical analysis results for the mayonnaise samples are given in Table 2. According to the moisture analysis results for the mayonnaise samples, moisture values ranged from 18.86% to 28.31%. A significant difference was identified for the % moisture values of the mayonnaise samples ($p<0.05$). The lowest % moisture rate was in WYMN, while the highest % moisture rate was in PMYN ($p<0.05$).

Table 2. Some chemical and physical analysis results of mayonnaise samples.

Mayonnaise samples	Moisture (%)	Ash (%)	Protein (%)	pH	TA	Oil (%)	Emulsion stability %	Color		
								*L**	*a**	*b**
CMYN	20.17 ± 0.02^{c}	1.80 ± 0.01^{d}	2.58 ± 0.28^{c}	4.21 ± 0.01^{c}	0.35 ± 0.02^{d}	80.90 ± 0.27^{a}	99.20 ± 0.0^{a}	87.71 ± 0.03^{a}	-0.73 ± 0.03^{c}	20.29 ± 0.02^{d}
WMYN	18.86 ± 0.12^{d}	1.91 ± 0.01^{c}	4.65 ± 0.02^{b}	4.32 ± 0.00^{b}	0.66 ± 0.01^{b}	68.34 ± 2.98^{b}	79.87 ± 0.4^{c}	85.32 ± 0.03^{a}	-1.24 ± 0.03^{d}	21.61 ± 0.07^{d}
PMYN	28.31 ± 0.02^{a}	2.19 ± 0.03^{b}	7.14 ± 0.17^{a}	4.08 ± 0.01^{d}	1.34 ± 0.06^{a}	42.75 ± 1.76^{c}	90.96 ± 0.19^{b}	79.36 ± 0.10^{ab}	-0.37 ± 0.06^{b}	26.57 ± 0.07^{b}
CCMYN	23.21 ± 0.03^{b}	2.13 ± 0.05^{b}	6.90 ± 0.04^{a}	4.97 ± 0.00^{a}	0.21 ± 0.00^{e}	44.79 ± 1.78^{c}	96.80 ± 0.04^{a}	82.08 ± 0.04^{a}	-0.17 ± 0.09^{a}	25.28 ± 0.04^{c}
MMYN	22.9 ± 0.02^{b}	2.42 ± 0.01^{a}	7.28 ± 0.06^{a}	4.38 ± 0.00^{b}	0.58 ± 0.01^{c}	35.58 ± 0.69^{d}	93.83 ± 0.03^{ab}	77.28 ± 0.16^{b}	-0.17 ± 0.06^{a}	28.67 ± 0.23^{a}

Different letters in the same column indicate a significant difference between the samples. The level of significant difference is ($p<0.05$). CMYN: control; WMYN: whey protein; MMYN: mango flour: whey protein; CCMYN: coconut flour: whey protein; PMYN: pineapple flour: whey protein.

Because of the % moisture analysis results, the addition of whey powder was observed to reduce % moisture values. While the % moisture analysis for CYMN found 20.17% moisture, the WMYN sample had moisture % value which fell to 18.86%. In a study by Satrawian *et al.* (2022) % moisture value for the control sample was 19.05%, while this value was 15.81% for mayonnaise with whey protein added. Mayonnaise containing fruit powder appears to have higher moisture content (Satriawan et al., 2022). Ash analysis results of mayonnaise samples given in Table 2 are between 1.80% and 2.42%. The addition of whey and fruit flours to the mayonnaise samples caused statistically significant differences in the % ash values ($p<0.05$). The lowest ash proportion was identified in the CMYN sample, with highest ash in the MMYN mayonnaise sample. While the % ash rate in the control sample was 1.80%, the % ash rate increased to 2.42% in the mayonnaise with mango powder and whey protein powder added. The % protein analysis results are given in Table 2. According to the analysis results for % protein in mayonnaise samples, the % protein in the samples was identified in the range of 2.58 to 7.28%. According to the analyses, the addition of whey protein to the mayonnaise had a significant effect on the protein content values ($p<0.05$). The lowest protein rate was identified in CMYN with highest protein in the MMYN sample ($p<0.05$). Among the mayonnaise samples with fruit flour addition, the highest protein was observed in the MMYN sample. In this study, the WMYN mayonnaise sample containing whey powder was identified to have higher protein content than the control mayonnaise. Whey protein concentrates, with their high protein content (65–70%) and valuable amino acids (Ganju & Gogate, 2017), are seen to enhance the nutritional properties of the products they are added to. The pH and TA results for the mayonnaise samples are given in Table 2. Analysis performed on the first day observed that the pH values were between 4.07 and 4.97. The mayonnaise containing whey and fruit flours had statistically significantly different pH and total acidity values ($p<0.05$). The highest pH value was found in the CCMYN sample, with the lowest value in the PMYN sample. The acidity values were in the interval from 0.21 to 1.34%. A statistically significant difference was identified for the acidity values of the mayonnaise samples ($p<0.05$). The lowest value was found in the CCMYN mayonnaise, with highest for the PMYN mayonnaise. Tropical fruits have differences in pH values. In studies, the pH of pineapple was shown to vary from 4.5 to 3.7 according to the maturation of the fruit (Uan-On, 2009), mango has pH from 4.2 to 4.5 (Vu *et al.*, 2023), and coconut has a pH of about 6.20 (Santos *et al.*, 2013). Accordingly, the pH of fresh egg yolks is generally around 6.0–6.9 according to conditions (Xiong *et al.*, 2000). In addition, studies confirmed that the proportion of egg yolk to acidifying material is the basic factor determining the pH of mayonnaise. Studies showed that the pH value of low-fat mayonnaise will increase linked to the increased percentage of whey protein added. The pH of mayonnaise was determined to affect the emulsion structure and stability (Nidhal *et al.*, 2022).

Color analysis findings

Mayonnaise is one of the most favored sauces among young people. The color of mayonnaise is generally pale yellow or sometimes white with different consistencies (Raikos *et al.*, 2016). The L^*, a^*, and b^* values obtained because of color analysis of mayonnaise samples are given in Table 2. The CMYN samples had mean L^* value +87.7, a^* value −0.73, and b^* value +20.29; WMYN mayonnaise had mean L^* value +85.29, a^* value −1.23, and b^* value +21.57; CCMYN had mean L^* value +82.0, a^* value −0.13, and b^* value 25.27; PMYN had mean L^* value +79.36, a^* value −0.37, and b^* value +26.57; MMYN had mean L^* value +77.28, a^* value +0.1, and b* value +28.67. Among mayonnaise samples, the brightness samples were the control sample, mayonnaise containing whey powder, and mayonnaise containing coconut flour. Whey powder gave a green color with a low a^* value, while fruit flour gave it a color closer to red. This situation may be because of the high carotenoids provided by the fruit flours (Santos *et al.*, 2022). Adding fruit flour resulted in a darker yellow color. The highest yellowness was observed in the mayonnaise containing mango. It appeared that whey did not provide a very effective increase in the yellow color. Mango flour increased the yellowness of mayonnaise compared to the other samples. The control mayonnaise appeared to have the same yellow color as the mayonnaise containing whey powder. While CMYN mayonnaise had a bright yellow color, MMYN mayonnaise had a darker yellow color.

Emulsion stability analysis and microstructure

The total fat % content of mayonnaise samples is given in Table 2. The mayonnaise samples containing exotic fruit flours and whey were found to have statistically significant differences for % fat content ($p<0.05$). The fat content of mayonnaise varied from 35.58 to 80.90%. The highest fat content was in the CMYN control sample, with the lowest fat content in MMYN mayonnaise containing mango flour and whey powder. The whey powder content was effective in lowering the fat proportion in mayonnaise samples. It appeared that tropical fruit flours and whey powder had higher effect in reducing the fat in mayonnaise. Mayonnaise with less than 65% fat content is defined as "reduced fat mayonnaise" (Ma & Boye, 2013). In this study, the PMYN, CCMYN, and MMYN mayonnaise samples had 35–40% fat content. It appeared that the tropical fruit flours were effective in reducing the fat rate. Fat-free compounds like gums, starches, and proteins, with different functions in reducing fat, are included in reduced-fat products. A new oil substitute should not just improve the processing functions but is also expected to contribute nutritional benefits (Laneuville *et al.*, 2005; McClements & Demetriades, 1998; Ward, 1997). In the study, the fat proportion in the control sample was 80.9%. Adding whey protein and fruit powders lowered this rate to 35.58%. A study by Komaç *et al.* (2018) found the fat proportion in the control sample was 78.46%, while mayonnaise with added avocado puree had fat rates lowered to 42.18% (Komac, 2018). The emulsion stability of different mayonnaise formulations is given in Table 2. The emulsion stability was described as affecting droplets becoming cream-like, flocculation, and coalescence. In high-fat products, oil droplets cannot flow freely, and in low-fat mayonnaise the movement of oil droplets is generally reduced by adding thickening compounds like starch or gum in the water phase (Mcclements, 2007). Emulsion stability was highest for the control sample CMYN in addition to the CCMYN and MMYN mayonnaise samples. The lowest emulsion stability was determined in the WMYN mayonnaise containing whey powder. It appears that fruit flours and whey powder mixtures were more effective on emulsion stability. Studies have reported that interactions between different polysaccharides, such as protein gum and pectin, significantly improve the stability of mayonnaise emulsion (Abdoollahi *et al.*, 2025; Ghoush *et al.*, 2008; Herald *et al.*, 2009). The combination of whey powder and fruit flour may have improved emulsion stability by forming a gel-like structure in mayonnaise samples.

Light microscope images of mayonnaise samples containing control and whey protein powder and different fruit flours are presented in Figure 1. It is seen that the oil droplets are homogeneously distributed in the control mayonnaise. In WMYN mayonnaise, the droplets are larger and more dispersed than in the previous classic mayonnaise. As seen in the stained microscope image, the droplets coalesce, resulting in a structure with reduced stability and homogeneity. The substituted mayonnaise emulsion system containing MMYN-encoded mango flour and whey protein resulted in smaller, well-distributed droplets, indicating improved stability. The mango flour, with its dietary fiber content, likely acts as a thickener and stabilizer (Müller-Maatsch *et al.*, 2016). Studies have shown that fiber content increases emulsion stability (Ketenoglu *et al.*, 2014). CCMYN mayonnaise containing coconut and whey appears to have a higher density of irregular, variable-sized droplets. One study reported that coconut particle sizes range from large to small (Tangsuphoom & Coupland, 2008). In WMYN mayonnaise containing pineapple and whey protein, smaller and more regular droplets were observed to be evenly distributed in the emulsion matrix. The stained

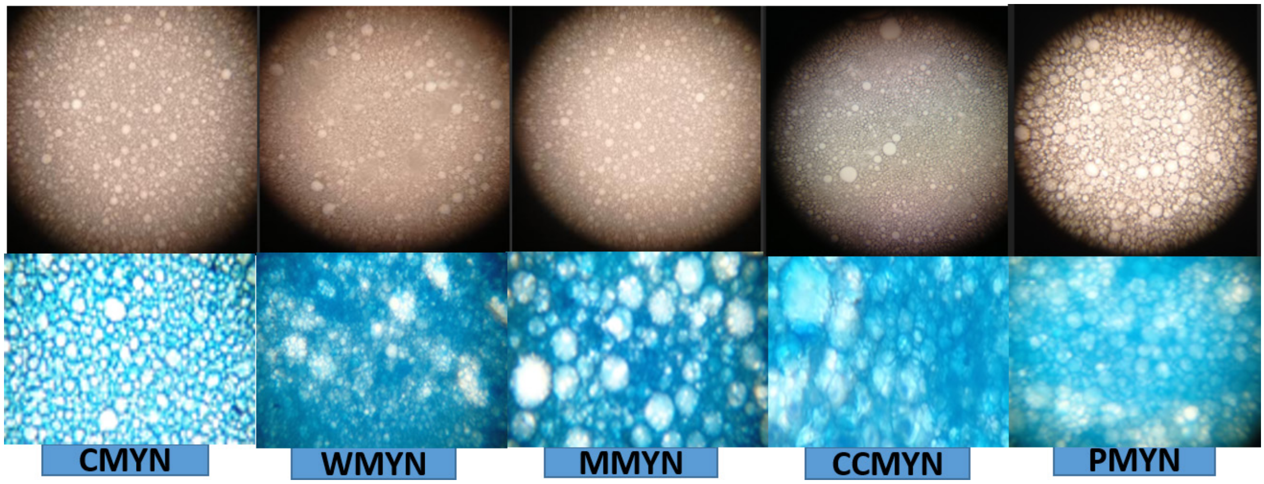

Figure 1. Light microscope images of control mayonnaise and exotic fruit flour – whey protein enriched mayonnaise samples, respectively, CMYN: control; WMYN: whey protein; MMYN: mango flour: whey protein; CCMYN: coconut flour: whey protein; PMYN: pineapple flour: whey protein.

microscope image also showed a more pronounced homogeneous distribution of equal sizes. Moreover, from a microstructural perspective, there was no significant oil droplet coalescence, indicating that the emulsion stability was optimal. A structure similar to the control mayonnaise was observed. The high viscosity prevents the oil droplets from flowing, and it has been determined that an elastic structure prevails in emulsions with a G′ higher than the G″ (Feng *et al.*, 2023; Sarbon *et al.*, 2015; Zhang *et al.*, 2024). As seen in Table 4, the higher viscosity and G″ of mayonnaise containing mango and coconut indicate an increased emulsion stability. In mayonnaise containing pineapple flour, which has a more homogeneous structure in its microscopic appearance, low viscosity and viscoelastic structure may limit emulsion stability in the long term.

Rheological properties of mayonnaise

Rheology is a property mainly related to the quality and stability of a food emulsion during storage. In the study, rheological measurements were performed for mayonnaise produced with different formulations as control and with different fruit powders and whey. The graph obtained as a result of these measurements is shown in Figure 2 with the consistency index (K) values given in Table 3.

All samples generally had flow characteristics consistent with the best Herschel–Bulkley model and according to the model values had high correlation (R^2=0.99). When Table 3 is investigated, the viscosity values of the samples were between 0.22 and 40.99 Pas^n, where n had values varying from 0.26 to 0.93. The highest viscosity was identified for the CCMYN mayonnaise with a value of 40.99 Pas^n, while the lowest viscosity was for the CMYN control mayonnaise with a value of 0.22 Pas^n. The viscosity values of mayonnaise samples varied according to differences in the fruit flours. Mayonnaise containing whey was found to have higher consistency coefficient index than the CMYN control mayonnaise. Different fruit powders were found to have different consistency coefficient indices, with the highest value observed in the CCMYN mayonnaise sample and the lowest value in the PMYN mayonnaise sample. The flow behavior index (n) was observed to be less than 1 for all samples (n<1). As the flow index reduces, the product tends to become more sensitive to shear speed. Mayonnaise samples containing fruit flour and whey were found to have lower flow behavior index compared with the control mayonnaise.

Dynamic rheological properties were examined to assess the solid or liquid features of the mayonnaise samples. The gel-like features of the mayonnaise samples increased with the increasing frequency of G′ and G″ values. As can be seen in Figure 2, the G′ value was higher than the G″ values for all samples in all frequency intervals. This shows that the solid-like behavior was dominant compared to the liquid character in all mayonnaise samples. In addition, the G' and G" values increased compared to control because of fruit powders and whey protein powder content. High G' value is related to droplet size and how compact the droplets are. Table 3 presents the K′, K′, n′, and n″ values calculated using the power law model. The model was confirmed by R^2 values larger than 0.95. As seen in Table 3, the K′ and K″ values were in the interval 51.77–282.31 and 16.15–61.21, while the n' and n" values were in the interval 0.15-0.28 and 0.29–0.46, respectively. The K' values are higher than

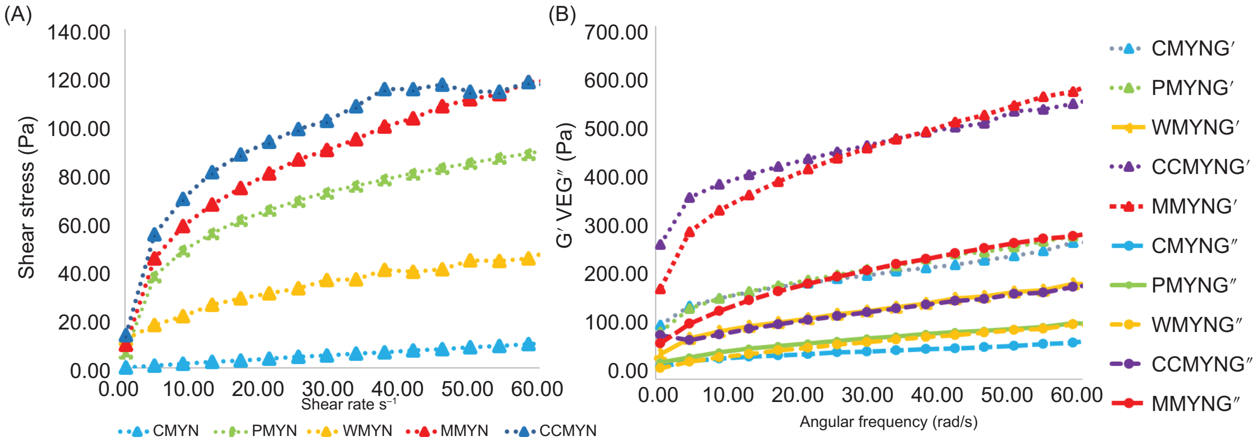

Figure 2. Flow behavior and rheological properties of mayonnaise. (A) Steady shear rheological behavior. (B) G′ and G″ values of mayonnaise samples, CMYN: control; WMYN: whey protein; MMYN: mango flour: whey protein; CCMYN: coconut flour: whey protein; PMYN: pineapple flour: whey protein.

Table 3. Steady shear power-law parameters of mayonnaise and viscoelastic behavior.

Steady shear power-law parameters of mayonnaise			
Mayonnaise samples	Consistency coefficient K (Pas^n)	Flow behavior index n	R^2
CMYN	0.22	0.93	0.99
WMYN	10.24	0.37	0.99
PMYN	24.23	0.32	0.99
MMYN	28.12	0.35	0.99
CCMYN	40.99	0.26	0.99

Viscoelastic behavior of the low-fat mayonnaise						
	G′ (Pa)			G″ (Pa)		
	K′	n′	R^2	K″	n″	R^2
CMYN	110.13	0.18	0.99	21.74	0.29	0.97
WMYN	51.77	0.28	1.00	16.15	0.46	0.99
PMYN	97.52	0.24	1.00	26.22	0.34	0.99
CCMYN	282.31	0.15	1.00	50.89	0.30	0.92
MMYN	195.25	0.25	1.00	61.21	0.38	1.00

CMYN: control; WMYN: whey protein; MMYN: mango flour: whey protein; CCMYN: coconut flour: whey protein; PMYN: pineapple flour: whey protein.

the K" values, which shows that these mixtures have viscoelastic properties. Frequency data show that low-fat mayonnaise samples display properties similar to standard mayonnaise. Generally, emulsions with higher fat content are expected to have higher G′ values (Ma & Barbosa-Cánovas, 1995). The CCMYN and MMYN samples had the highest storage module. Water holding has the ability to reduce available free water and as a result increase the viscosity of emulsions (Sheldrake, 2003). The viscosity increase with the addition of fruit flour may be related to the high fiber content of the flour, such as pectin, which acts as a thickening agent. Mistrianu *et al.* (2022) found that the addition of beet by-product powder to mayonnaise samples significantly increased the viscosity and contributed to the development of a cream-like consistency (Lourenço *et al.*, 2016). In this situation, formation of a more resistant, very viscous, and solid-like structure was stated to require higher stress to initiate flow (Jadhav *et al.*, 2022; Thaiudom & Khantarat, 2011). Studies have shown that whey has emulsifying properties because of its ability to adsorb onto the surface of oil droplets (Shimizu *et al.*, 1981). With the addition of fiber, it provides emulsion formation, gelation, stabilization, and water-binding properties in foods (Elleuch *et al.*, 2011). The differing dietary fiber contents of pineapple, mango, and coconut flours may affect emulsification. Dietary fiber has been shown to increase water-binding capacity (Elleuch *et al.*, 2011), and mayonnaises containing mango and coconut may have higher dietary fiber content (Table 3), higher water-binding capacity, and higher whey proteins, resulting in higher viscosity and G″ formation by enhancing gel structure (Bi *et al.*, 2025). Although pineapple's low acidity and natural bromelain enzyme (Lourenço *et al.*, 2016) resulted in lower viscosity and G' residues compared to mayonnaise containing mango and coconut, it still provided a similar structure to the control mayonnaise.

Total Phenolic Matter Content (TPC), DPPH, ABTS$^{•+}$ and Dietary Fiber Content of Mayonnaise

The total phenolic matter content and antioxidant capacity (DPPH and ABTS$^{•+}$) of mayonnaise samples are given in Table 4. TPC in CMYN, WMYN, PMYN, CCMYN, and MMYN samples was determined to be 5.45% to 37.68%. The lowest total phenolic rate was in CMYN samples, with the highest TPC in the MMYN samples ($p<0.05$). The DPPH analysis results are given in Table 4.

Table 4. TPC, DPPH, ABTS$^{\bullet+}$, and dietary fiber analysis results of mayonnaise samples.

Mayonnaise samples	TPC (mg GAE /100g)	DPPH (mg TE/100 g)	ABTS$^{\bullet+}$ (mgTE /100g)	Dietary Fiber %
CMYN	5.45±0.17^{d}	19.22±0.63^{b}	23.66±0.90^{d}	2.90 ± 0.20^{d}
WMYN	10.38±0.48^{c}	20.9±0.13^{b}	31.96±0.80^{c}	2.28 ± 0.16^{e}
PMYN	21.73±0.60^{b}	27.95±0.33^{a}	50.61±0.65^{a}	16.72 ± 1.17^{c}
CCMYN	13.54±0.33^{c}	20.34±0.3^{b}	40.91±0.75^{b}	22.38 ± 1.57^{a}
MMYN	37.68±1.48^{a}	25.25±0.20^{ab}	46.81±0.25^{ab}	16.43 ± 1.15^{b}

Different letters in the same column indicate a significant difference between the samples. The level of significant difference is (p<0.05). CMYN: control; WMYN: whey protein; MMYN: mango flour: whey protein; CCMYN: coconut flour: whey protein; PMYN: pineapple flour: whey protein.

According to the DPPH analysis results for the mayonnaise samples, the DPPH rates were determined to be in the interval from 17.73 to 23.44%. The lowest DPPH value was in the CMYN sample, with the highest DPPH value in PMYN (p<0.05). According to ABTS$^{\bullet+}$ analysis results for mayonnaise samples, the ABTS rates in CMYN, WMYN, PMYN, CCMYN, and MMYN samples varied from 23.66% to 50.61%. The ABTS$^{\bullet+}$ analysis results are given in Table 4. The lowest ABTS percentage was in CMYN, with the highest ABTS$^{\bullet+}$ percentage in PMYN (p<0.05). Fruit flours increased the antioxidant capacities of the mayonnaise samples, with positive contribution to nutritional features. A study investigated the phenolic and antioxidant features of mayonnaise prepared using 1.5% (a/a) lupin and faba proteins instead of egg yolk and also added apple, nectarine, pear, and peach fruit flours. The mayonnaise with fruit flour was determined to have higher antioxidant effect than standard mayonnaise. This situation was explained by the high content of bioactive compounds like anthocyanins, phenolic acids, and flavonols in fruit (Espinosa-Solis *et al.*, 2019; Vieira M. *et al.*, 2023). A similar study indicated that the addition of 5% passion fruit increased the TPC (49.36 mg/mL) and DPPH (29.00%) capacity of mayonnaise. Fat-rich foods require antioxidant additives to protect against oxidative degradation (Ahamad Zabidi *et al.*, 2024). Exotic fruit flours in mayonnaise not only affect emulsion stability but also contribute to oxidative resistance through their natural antioxidant capacity.

The dietary fiber content of the mayonnaise samples is given in Table 4. Dietary fiber content varied from 2.28% to 16.72%. It was observed that fruit flours statistically significantly affected the dietary fiber content of mayonnaise samples (p<0.05). The highest dietary fiber was in the CCMYN and MMYN mayonnaise samples, with the lowest in the control mayonnaise CMYN and in the WMYN sample containing whey protein. The mayonnaise samples containing coconut and mango flours were determined to have higher dietary fiber than the mayonnaise sample containing pineapple flour. Pineapple was determined to have an average of 0.5 to 1.5 g/100 g dietary fiber based on variety in fresh fruit (Ancos *et al.*, 2016). Dietary fiber is an important functional nutrition source.

Sensory properties of mayonnaise

Five different mayonnaise samples were evaluated by 40 panelists based on 12 parameters: brightness, color, consistency (in the mouth and spoon), smoothness, sweetness, oiliness, rancid taste, odor, aroma, taste, and general likeability. The sensory analysis results of the mayonnaise are shown in Figure 3. The mean score for the brightness of the mayonnaise samples ranged from 3.4 to 4.5. Differences between the brightness scores were found to be statistically significant (p<0.05). Among the mayonnaise samples, the most favored mayonnaise in terms of brightness was the control mayonnaise, CMYN mayonnaise. The lowest-rated mayonnaise in terms of brightness was the MMYN mayonnaise containing mango flour and whey powder. The average consistency (mouthfeel) score for the reduced-fat mayonnaise samples ranged from 3.37 to 4.4. Differences between consistency (mouthfeel) scores were statistically significant (p<0.05). Among the mayonnaise samples, the most popular in terms of consistency (mouthfeel) were CMYN, WMYN, and PMYN mayonnaises. The lowest-rated was MMYN mayonnaise, which contains mango flour and whey powder. The average consistency (in the spoon) score for the reduced-fat mayonnaise samples ranged from 3.23 to 4.13. CMYN and WMYN were liked the most, and MMYN, CCMYN, and PMYN mayonnaises containing fruit flour and whey were found to be statistically similar (p>0.05). The mean score for smoothness of reduced-fat mayonnaise samples varied between 2.97 and 4.17. Differences between the smoothness scores were found to be statistically significant (p<0.05). Among the mayonnaise samples, the most liked mayonnaises in terms of smoothness were the control mayonnaise, CCMYN mayonnaise, and PMYN mayonnaise containing pineapple flour and whey powder. The least liked mayonnaise was MMYN mayonnaise containing mango

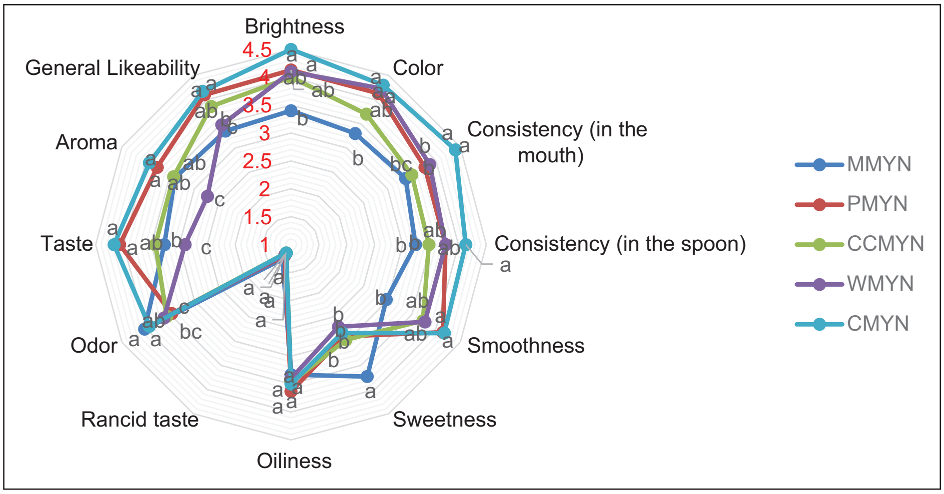

Figure 3. Sensory properties of mayonnaise. CMYN: control; WMYN: whey protein; MMYN: mango flour: whey protein; CCMYN: coconut flour: whey protein; PMYN: pineapple flour: whey protein. Lowercase letters for each attribute indicate significant differences (*p* < 0.05).

flour and whey powder. The mean score for oiliness of reduced-fat mayonnaise samples varied between 3.3 and 3.6. Among the mayonnaise samples, the scoring for oiliness was found to be statistically insignificant (p>0.05). The mean odor score for the reduced-fat mayonnaise samples varied between 3.57 and 4.03. Differences between the odor scores were statistically significant (p<0.05). Among the mayonnaise samples, the most favored odor scores were CMYN, MMYN, and PMYN. The least favored mayonnaise scores were WMYN and CCMYN. The average taste score for the reduced-fat mayonnaise samples ranged from 2.9 to 4.17. Differences between the taste evaluation results were found to be statistically significant (p<0.05). Among the mayonnaise samples, CMYN and pineapple flour enriched PMYN mayonnaise, received the highest flavor scores. The least popular taste was WMYN mayonnaise containing whey powder. The mean color score for the reduced-fat mayonnaise samples varied between 3.3 and 4.13. Significant differences were found in the color scoring results (p<0.05). Among the mayonnaise samples, the most popular color samples were CMYN, WMYN, and PMYN mayonnaises. The least popular mayonnaise was MMYN mayonnaise containing mango flour and whey powder. The mean score for the rancid taste of reduced-fat mayonnaise samples varied between 1.1 and 1.3. The rancid taste scores were statistically similar among the mayonnaise samples, and the rancid taste was found to be insignificant (p>0.05). The average score of the evaluation of reduced-fat mayonnaise samples in terms of aroma varied between 2.73 and 3.93. Statistically significant differences were determined between the scoring results in terms of aroma (p<0.05). Among the mayonnaise samples, the most liked in terms of aroma were CMYN and PMYN mayonnaise. The least liked mayonnaise in terms of aroma was WMYN mayonnaise. The average score of the evaluation of reduced-fat mayonnaise samples in terms of overall liking varied between 3.35 and 4.17. The differences between the scoring results in terms of overall liking were found to be statistically significant (p<0.05). Among the mayonnaise samples, the most liked in terms of overall liking were PMYN and CMYN. The least liked mayonnaise was MMYN.

Microbial quality of mayonnaise

Figure 4 shows the changes in microbial counts of mayonnaise treatments during storage. Microbial growth in mayonnaise samples during the fifth, sixth, seventh, and eighth weeks of storage is shown in Figure 4. According to the results, total yeast and mold counts were determined to be below 1 log for all treatments up to 5 weeks after storage. While total counts varied between 3.32 and 4.69 log CFU/mL in the fifth week, they increased between 3.99 and 5.23 log CFU/mL in the sixth week, and increased to 4.8 and 6.74 log CFU/mLin the seventh week, reaching high values of 6.37 and 7.88 log CFU/mLin the eighth week. During storage, mayonnaise samples containing fruit flour showed lower microbial growth compared to control and whey mayonnaise. The lowest growth was observed in mayonnaise containing pineapple flour. Studies on plant origin have demonstrated that many fruits possess strong natural antibacterial activity because of numerous compounds such as alkaloids, flavonoids, steroids, terpenoids, phenolic compounds, antioxidants, etc. A study has shown that malic acid in mango, pineapple, and papaya juices has antimicrobial activity against *Listeria monocytogenes*, *Salmonella enteritidis*, and *Escherichia coli* (Lima *et al.*, 2015;

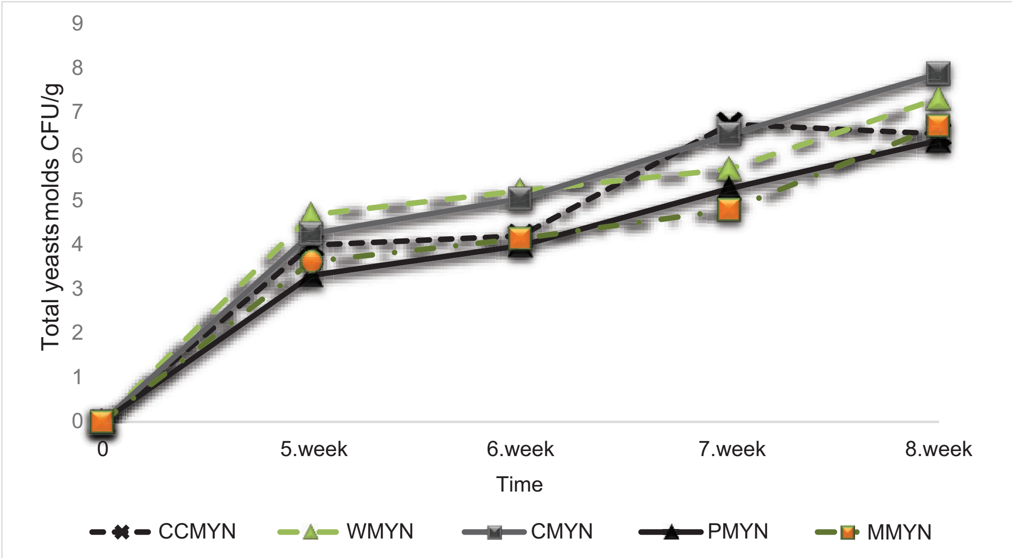

Figure 4. Total yeast and mold counts of mayonnaise enriched with control, whey protein powder, and whey protein-fruit flours during storage. CMYN: control; WMYN: whey protein; MMYN: mango flour: whey protein; CCMYN: coconut flour: whey protein; PMYN: pineapple flour: whey protein.

Mat *et al.*, 2022; Rathnayaka, 2013; Sayago-Ayerdi *et al.*, 2021). It has been stated that pineapple and mango fruit have lower pH values than coconut. Fruits contain various organic acids, giving them an acidic character, which is effective in extending the shelf life of fruit-containing products (Kothalawala *et al.*, 2018; Liu *et al.*, 2013). Among exotic fruits, pineapple had the lowest pH content, reducing yeast and mold growth throughout storage.

Conclusions

Whey, combined with fruit flours, reduced the fat content of mayonnaise and increased its nutritional value by increasing its protein, dietary fiber, and phenolic antioxidant content. Fruit flours increased the yellowness of mayonnaise. Mayonnaises containing coconut and whey, and mayonnaises containing mango and whey, produced a thicker mayonnaise than mayonnaises containing pineapple. Whey and fruit flours together increased emulsion stability in mayonnaises. In sensory evaluations, pineapple-enriched mayonnaises were closest in overall taste to control mayonnaises. Fruit flours increased the shelf life of mayonnaises. Generally speaking, while fruit flours combined with whey improved the nutritional quality of mayonnaise, they created differences in technological quality (viscosity and emulsion stability). Among fruit flours, pineapple flour–containing mayonnaises were found to have similar viscosity, viscoelasticity, and microscopic structure to control mayonnaises. Emulsion stability can be examined depending on storage conditions. Whey protein concentrates can be said to have the potential to enhance the nutritional properties of the low-fat mayonnaise they are added to, as well as the technological quality. Future research should explore strategies for storage stability by providing optimal optimization conditions.

Ethical Statement

Sensory evaluation was conducted by trained panelists, food engineering students, and faculty members, who verbally consented to participate in the study beforehand. Prior to the start of the process, the panelists were informed about how they would be evaluating the study. Participation in the evaluation was voluntary. No ethics committee approval is needed.

Mandatory Disclosure on Use of Artificial Intelligence

The authors declare that no AI-assisted tools were used in the preparation of this manuscript. All references have been manually verified for accuracy and relevance.

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Authors Contributions

Elif Cakir was in charge of supervision, conceptualization, investigation, methodology, writing—review and editing, data curation, formal analysis, and writing—original draft; Muhammed Sahin was in charge of methodology, investigation, formal analysis, and writing—original draft; and Hatice Bekiroglu was in charge of co-supervision, methodology, formal analysis, and writing—review and editing.

Conflict of Interest

The authors declare that they do not have any conflict of interest. This research was produced from Muhammed Sahin's master's thesis.

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