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Egg-free low-fat mayonnaise from virgin coconut oil

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Abstract:
Introduction. Mayonnaise is a widely consumed product all over the world. Nowadays, the number of vegetarians, egg allergy cases, and heart diseases are increasing. This makes manufacturers develop alternatives. The research objective was to select the optimal concentration of emulsifiers for egg-free mayonnaise made from virgin coconut oil.
Study objects and methods. We produced 20 egg-free mayonnaise samples with different amounts of emulsifiers. We also determined physicochemical properties of the samples, as well as performed proximate and statistical analyses.
Results and discussion. The response surface methodology made it possible to define such parameters as viscosity, stability, and firmness as affected by the following concentrations: cashew nut protein isolates – 5–15%, xanthan gum – 0–1%, and modified starch – 0–0.5%. The optimal values of emulsifiers were obtained as follows: cashew nut protein isolates – 13 g, xanthan gum – 1.0 g, and modified starch – 0.4 g. The optimized mayonnaise had the following parameters: viscosity – 120.2 mPa·s, stability – 98.7%, and firmness – 25 g. The study revealed no significant differences ($P > 0.05$) between the actual and predicted data, which confirmed the efficiency of the suggested models.
Conclusion. The obtained low-fat egg-free mayonnaise was relatively similar to the traditional commercial products. However, virgin coconut oil should be emulsified with a combination of cashew nut protein isolates, modified starch, and xanthan gum.

Keywords: Mayonnaise, emulsion, egg yolk, emulsifier, protein isolates, cashew nut, virgin coconut oil

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INTRODUCTION

Mayonnaise is an emulsion of oil in water. Therefore, dietary mayonnaise has a smaller dispersed step and larger water content [1–3]. Mayonnaise consists of 60–80% fat [4]. Conventionally, it contains egg yolk, oil, lemon juice or vinegar, and seasonings, e.g. salt, mustard, paprika, sweeteners, etc. Three main components in mayonnaise perform as different phases in the formulation: oil is the dispersed phase, water is the continuous phase, and egg yolk is the emulsifier [5, 6]. Mayonnaise is fat-free if its fat level is at least 50% lower than that of standard mayonnaise; mayonnaise is considered light if its fat level is 25% lower than standard [7].

Eggs are a common mayonnaise emulsifier because their emulsifying properties are perfect for mayonnaise production. However, the growing rates of vegetarianism, egg allergy, heart diseases, and production costs make producers look for egg-free formulation variants.

Furthermore, plant-based diets have gained popularity not only due to the health benefits they promise but as a way to reduce environmental footprint [8]. Therefore, new egg substitutes and egg-free products are of great importance in vegetarian food supplies [9]. In general, protein acts as a surfactant to reduce the surface tension between hydrophilic and lipophilic materials in food systems and stabilize emulsions. Cashew nut protein isolates can serve as an egg alternative and a fat replacer agent due to their excellent emulsifying property [10]. However, cashew nuts are a much less popular plant protein, despite their excellent sensory and nutritional benefits [11].

Several studies have evaluated plant-based emulsifiers as potential substitutes for eggs. Chetana *et al.* reported egg-free mayonnaise of rice bran oil and sesame oil produced by replacing egg with xanthan gum [14]. Gaikwad *et al.* managed to replace egg yolk with skim milk powder [15]. In another study, wheat germ protein isolate and xanthan gum substituted egg yolk to produce low-cholesterol mayonnaise with acceptable characteristics [16]. Modified starch can also serve as an alternative to fat and eggs in low-fat mayonnaise [17]. Among vegetable oils, coconut oil obtained from coconut kernel (*Cocos nucifera* L.) was reported to have antibacterial and antioxidant biological activities [18]. Virgin coconut oil is widely used in other vegetable oils since it has many health benefits. Virgin coconut oil decreases total cholesterol, triglycerides, phospholipids and low-density lipoprotein (LDL) cholesterol, while increasing high-density lipoprotein (HDL) cholesterol in the blood [19].

Although many studies reported this or that kind of egg-free mayonnaise produced from various oils and emulsifiers, none of them featured the combination of cashew nut protein isolates, xanthan gum, and modified starch. Consequently, the current study aims at selecting the optimal concentration of emulsifiers of cashew nut protein isolates, xanthan gum, and modified starch to produce egg-free virgin coconut oil mayonnaise and compare its properties with commercial mayonnaise products.

STUDY OBJECTS AND METHODS

Materials. Table 1 shows the ingredients of egg-free Lady's Choice mayonnaise (Bangi, Selangor) used as a reference sample. Xanthan gum, cashew nut protein isolates, and modified starch (maize) were purchased from Sigma-Aldrich Co. (St. Louis, MO, USA).

Experimental design. The methods of response surface methodology and central composite design were used with three independent variables of emulsifiers, namely cashew nut protein isolates (5–15%) (X_c), xanthan gum (0–1%) (X_x), and modified starch (0–0.5%) (X_m) (Table 2). Viscosity (Y_1), stability (Y_2), and firmness (Y_3) served as response variables.

Preparation of egg-free virgin coconut oil mayonnaise. The low-fat and egg-free mayonnaise-like emulsion gel was prepared according to Mozafari *et al.* with some modifications [20]. Briefly, a fixed amount of distilled water, lemon juice, mustard, sugar, acetic acid, and salt (Table 1) were mixed in a blender 8010S (Waring Commercial Torrington, USA), at medium speed for 3 min to achieve a smooth and creamy coarse-phase emulsion. Virgin coconut oil was then gradually added to the coarse-phase emulsion, followed by emulsifiers, i.e. cashew nut protein isolates, modified starch, and xanthan gum (Table 2). The mix (500 mL) was further homogenized at high speed for 2 min until smooth and creamy. All mayonnaise samples were transferred into 500-mL sterilized glass jars, capped, tightly sealed, and kept at room temperature (25 ± 2°C) prior further analysis.

Physicochemical properties. Physicochemical properties are given for the optimized formulation only.

Viscosity. The viscosity measurement followed the method developed by Makeri *et al.* [21]. It involved a rheometer HAAKE RheoStress RS600 (Thermo Electron Corporation, Karlsruhe, Germany) and a parallel stainless-steel plate with a 25-mm diameter at a 1-mm distance at 25°C. A sample of 10 mL was loaded onto the plate with extreme carefulness to prevent emulsion softening. The excess sample was carefully trimmed from the sensor edge with a thin blade [22]. The flow characteristics were determined at a temperature of 25°C and a shear rate of 1–100 s^{-1}. Each viscosity measurement was performed in triplicate, and mean ± SD values were plotted.

Texture. The texture of the egg-free virgin coconut oil mayonnaise was determined using a texture analyser (XT2i, Surrey, UK) following the method described in [23] with slight modifications. A total of 100 mg for each sample was placed in round plastic containers at a depth of 30 mm. The texture was determined using a P/35-cylinder probe (Stable Micro System, Surrey, UK). The force was measured in compression mode at fixed 75% strain at room temperature (25 ± 2°C). The test conditions included 10 mm penetration, 1 mm/s pre-test speed, as well as 1 and 10 mm/s test speed. The tests were performed in triplicate, and the mean values were tabulated.

Stability. The mayonnaise emulsion stability test was based on the amount of oil removed from the emulsion after centrifugation [24]. Briefly, 1.5 g of the sample was placed in a 25-mL centrifuge tube (Refrigerated centrifuge SIGMA 3-18K, Goettingen, Germany) and weighed (initial weight, F_0). The sample was heated for 30 min at 80°C in a shaking water bath at 120 rpm to form emulsion. After heating, the emulsions were centrifuged in a Thermo Sorvall Legend Micro 17 micro-centrifuge (Thermo Science, Waltham, MA) for

Table 1 Formulation for egg-free virgin coconut oil mayonnaise

Ingredients	Amount
Distilled water, mL	32.20
Virgin coconut oil, mL	32.20
Lemon juice, mL	16.10
Mustard, g	3.35
Sugar, g	2.68
Acetic acid, mL	2.68
Salt, g	0.13 g
Cashew nut protein isolates, X_c, %*	5–15
Xanthan gum, X_x, %*	0–0.1
Modified starch, X_m, %*	0–0.5

* % varies according to formulations generated using response surface methodology experimental design

Table 2 Response surface methodology experimental design of the three independent variables in egg-free mayonnaise formulations

Run order	Block	Cashew nut protein isolate (X_c)	Xanthan gum (X_x)	Modified starch (X_m)
1(c)	3	10(0)	0.5(0)	0.25(0)
2(c)	3	10(0)	0.5(0)	0.25(0)
3	3	15(1)	0.5(0)	0.25(0)
4	3	15(1)	1(1)	0.5(1)
5	3	5(–1)	0(–1)	0(–1)
6(c)	3	10(0)	0.5(0)	0.25(0)
7	3	5(–1)	0(–1)	0.5(1)
8	3	15(1)	1(1)	0(–1)
9(c)	1	10(0)	0.5(0)	0.25(0)
10	1	10(0)	0.5(0)	0.5(1)
11	1	10(0)	0.5(0)	0(–1)
12(c)	1	10(0)	0.5(0)	0.25(0)
13	1	5(–1)	1(1)	0.5(1)
14	1	15(1)	0(–1)	0.5(1)
15	2	10(0)	0(–1)	0.25(0)
16(c)	2	10(0)	0.5(0)	0.25(0)
17	2	5(–1)	1(1)	0(–1)
18	2	10(0	1(1)	0.25(0)
19	2	5(–1)	0.5(0)	0.25(0)
20	2	15 (1)	0(–1)	0(–1)

c is center point

5 min at 5000 rpm, and the top oil layer was extracted with a long-needle syringe. The precipitated fraction (F_1) was weighed, and the stability of the emulsions was estimated using the equation below:

$$\text{Percentage of emulsion stability (\%)} = \frac{F1}{F0} \times 100 \quad (1)$$

where F_0 is the Initial weight; F_1 is the weight of the precipitated fraction.

Water activity. The water activity test followed the calibration procedure. The sample cup was filled halfway with 3 g of mayonnaise sample using an AquaLab water activity meter (Model 3TE, Decagon Devices, USA). The sample chamber lid was sealed to reach vapor equilibrium. The dew point/temperature was later translated into water activity (A_w) reading.

pH measurement. The pH values were assessed by using a pH meter (S210 Seven compact, Mettler-Toledo Instrument Co., Ltd., Shanghai, China) at 25°C. The pH meter was adjusted at pH 7.01, 4.01, and 10.01 buffer solutions. The pH values were presented as a mean of three readings for one sample.

Proximate analysis. ***Moisture content.*** The moisture content was determined using the method developed by the Association of Official Analytical Chemists (AOAC) [25]. A sample of 5 g was put into a covered crucible and placed into a Memmert 800 oven (Schwabach, Germany). There it stayed for at least 7 h at 105°C; the temperature of the oven was constant. The crucible and its cover were set on the balance and weighed quickly and accurately. The weighing process was repeated to obtain constant weight. The moisture content was calculated based on the percentage of wet-weight:

$$\text{Wet} - \text{weight percentage (\%)} = \frac{(A-B)}{A} \times 100 \quad (2)$$

where A is the weight of sample before oven drying, g; B is the weight of dried sample after oven drying, g.

Protein content. This crude protein analysis method was designed by AOAC: it is based on the nitrogen (N) determination according to the Kjeldahl method in a Kjeltec 2100 Distillation Unit (Foss Tecator, Hoganas, Sweden) [25]. The protein content was calculated using the following formula:

$$\text{Protein content} \left(\frac{\text{g}}{100\text{g}}\right) = \text{Nitrogen content} \times F \quad (3)$$

where F is the protein factor (6.25, depends on the sample).

Fat content. The fat content was measured according to another AOAC method by petroleum ether extraction using a Soxtec System (2055 Soxtec Avanti; Foss Tecator, Höganäs, Sweden) [25]. The fat content was calculated by using the following formula:

$$\text{Fat content} \left(\frac{\text{g}}{100\text{g}}\right) = \frac{W_1 - W_2}{W_1} \times 100 \quad (4)$$

where W_1 is the sample weight, g; W_2 is the plain aluminum weight, g; W_3 is the aluminum with sample weight, g.

Ash content. The ash content was measured according to AOAC method: 10 g of the sample were placed into the crucible [25]. After recording the weight, it was put into a muffle furnace at 550°C. The sample burned for at least 2 h to obtain permanent weight, until no black particles. Next, the crucible and ash were cooled in the desiccators. Finally, the crucible was weighed together with the ash.

$$\text{Ash percentage (\%)} = \frac{(\text{a} + \text{b}) - \text{b}}{\text{c}} \times 100 \quad (5)$$

where a is the weight of ash; b is the weight of crucible; c is the weight of sample.

Carbohydrates content. The carbohydrate content was determined by extracting the protein, fat, moisture, and ash amount from 100%.

Statistical analysis. Minitab 17.0 (Minitab, Inc, State College Pennsylvania, USA) was used for optimization. The software programmed a face-centered composite design with three independent variables, namely cashew nut protein isolates (X_c), xanthan gum (X_x), and modified starch (X_m) at three coded levels (–1, 0, +1). The experiment involved six replicates at the center stage, with a total design of 20 experimental runs per sample. As a result, the effect of the two independent variables on the response surface was obtained as 3-D graphs of response. The polynomial regression model equation was used to define the performance of the response surface. The generalized response surface model looked as follows:

Table 3 Viscosity, stability, and firmness of egg-free virgin coconut oil mayonnaise produced with different percentages of cashew nut protein isolate, xanthan gum, and modified starch

Run order	Cashew nut protein isolate (X_c)	Xanthan gum (X_x)	Modified starch (X_m)	Viscosity, mPa·s (Y_v)	Stability, % (Y_s)	Firmness, g (Y_f)
1	10	0.5	0.3	104.2 ± 11.4	95.2 ± 2.2	24.6 ± 3.7
2	10	0.5	0.3	98.2 ± 4.9	89.3 ± 0.6	25.8 ± 1.6
3	15	0.5	0.3	101.6 ± 6.9	92.9 ± 1.0	22.3 ± 3.0
4	15	1	0.5	120.3 ± 22.8	100.0 ± 0.0	21.1 ± 2.0
5	5	0	0	47.8 ± 5.7	81.8 ± 0.7	9.2 ± 2.2
6	10	0.5	0.3	100.3 ± 15.6	93.9 ± 1.4	30.0 ± 2.0
7	5	0	0.5	88.2 ± 3.9	93.4 ± 1.8	17.3 ± 1.5
8	15	1	0	92.1 ± 3.6	96.4 ± 0.1	10.8 ± 1.4
9	10	0.5	0.3	106.8 ± 6.5	94.3 ± 0.9	22.3 ± 2.2
10	10	0.5	0.5	127.8 ± 19.4	95.8 ± 0.2	30.8 ± 3.1
11	10	0.5	0	84.0 ± 6.8	93.1 ± 1.6	17.5 ± 1.6
12	10	0.5	0.3	107.9 ± 9.0	93.9 ± 0.4	21.1 ± 1.8
13	5	1	0.5	122.8 ± 14.3	100.0 ± 0.0	16.6 ± 1.7
14	15	0	0.5	97.8 ± 4.8	94.2 ± 2.0	19.3 ± 5.1
15	10	0	0.3	72.8 ± 7.3	87.2 ± 1.3	19.4 ± 2.0
16	10	0.5	0.3	103.4 ± 14.4	94.9 ± 1.6	27.6 ± 2.7
17	5	1	0	93.4 ± 3.6	97.4 ± 1.2	6.7 ± 1.2
18	10	1	0.3	123.0 ± 6.5	95.2 ± 0.2	27.7 ± 1.8
19	5	0.5	0.3	98.1 ± 7.6	89.8 ± 3.1	18.0 ± 1.5
20	15	0	0	44.1 ± 3.1	79.2 ± 0.9	13.1 ± 2.1

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \quad (6)$$

where y is the response calculated by the model; β_0 is the constant regression; β_i, β_{ii}, β_{lj} are the linear, squared, and interaction coefficients, respectively; x_1, x_2 are the independent variables.

The responses were evaluated by multiple regressions and the square least method. A t-test was performed to compare the properties of both mayonnaise samples.

To validate the model, the experimental data were compared to the predicted values using the t-test at P-value = 1 and F-ratio = 0 for each response. Therefore, the model was declared suitable when no statistically significant difference was observed between the experimental and predicted values.

RESULTS AND DISCUSSION

Response surface methodology. The goal of the optimization was to obtain target values for responses, viscosity, and firmness, as well as to maximize the stability of the emulsion. The initial step was to decide on the experimental ranges for the independent variables. The levels of variation were selected according to a preliminary study. A uniform precision type central-composite design consisted of three variables, namely cashew nut protein isolates, xanthan gum, and modified starch. It had a three-level pattern with 20 runs and was prepared using the response surface methodology. The experimental design contained six cube center points, where six out of twenty runs were replications of the central points of all the factors. Twenty samples of egg-free virgin coconut oil mayonnaise were prepared based on the emulsifier quantity proposed in the experimental design. Other ingredients remained constant.

All twenty samples were measured for viscosity, stability, and firmness. Table 3 displays the variables, levels, and results obtained for all the responses. The analysis of variance was used to determine the significance of the linear, quadratic, and interaction effects, as well as the lack of fit value against the responses in the variables. The models fit well for all the response variables because they had acceptable levels of R^2 of more than 80%.

Table 4 illustrates the summary of R^2, %, P-value, and multiple regression equation of response for reduced regression equation model in the decoded units. The best model was the one with the highest R^2, lowest P-value (model), and the highest number of significant factors. The emulsifiers were optimized by identifying the desired response. The anticipated responses were designated based on the viscosity, stability, and firmness of commercial mayonnaise. These properties are known to be accepted by consumers. The reference mayonnaise underwent an analysis to obtain the desired response. The lack-of-fit in all the models had a P-value $\geq$ 0.05, i.e. the models were acceptable. The next step involved the P-value of individual factors of the quadratic and interaction effect against response. The factors with insignificant effects were removed to obtain a fitted reduced model equation.

In this study, X_c, X_x, and X_m were coded values for independent variables in the experiment, i.e. cashew

Table 4 Summary of reduced model equation for all responses

Response	R^2, %	*P*-value	Reduced model equation
Viscosity, mPa·s	97.5	0.00	$Y_v = 22.76 + 5.64\,X_c + 84.9\,X_x + 96.48\,X_m – 0.2760\,X_c{\cdot}X_c – 35.56\,X_x{\cdot}X_x – 36.5\,X_g{\cdot}X_m$
Stability, %	88.7	0.00	$Y_s = 81.89 – 0.033\,X_c + 15.74\,X_x + 24.42\,X_m – 20.40\,X_x{\cdot}X_m$
Firmness, g	80.9	0.00	$Y_f = –21.18 + 7.74\,X_c + 0.97\,X_x + 19.10\,X_m – 0.3683\,X_c{\cdot}X_c$

nut protein isolates, xanthan gum and modified starch, respectively. Likewise, Y_v, Y_s, and Y_f were coded values for viscosity, stability, and firmness dependent variables. All the initial and reduced model multiple regression equations used the code above.

Effect of independent variables on viscosity (Y_v). Viscosity measurement is essential to characterize the structure and stability of the food emulsion products, such as mayonnaise. Figure 1a shows that both the linear and square effects were significant for viscosity, while the overall model *P*-value was < 0.05 for both. The interaction effect of cashew nut protein isolates with xanthan gum and modified starch was not significant, with a *P*-value of 0.472 and 0.372, respectively.

The analysis of regression coefficient showed that viscosity experienced significant impact ($P < 0.05$) from the linear effect of cashew nut protein isolates (X_c), xanthan gum (X_x), modified starch (X_m), quadratic effect cashew nut – cashew nut ($X_c{\cdot}X_c$), xanthan gum – xanthan gum ($X_x{\cdot}X_x$), and interaction effect xanthan gum – modified starch ($X_x{\cdot}X_m$). The increased amount of these variables resulted in increased viscosity. The reduced model equation for viscosity was predicted as below:

$$Y_v = 22.76 + 5.64\,X_c + 84.9\,X_x + 96.48\,X_m – \\ – 0.2760\,X_c{\cdot}X_c – 35.56\,X_x{\cdot}X_x – 36.5\,X_x{\cdot}X_m \qquad (7)$$

The equation above was fitted using a second-degree polynomial model for independent variable effects of cashew nut protein isolates, xanthan gum, and modified starch on apparent viscosity response. The modified value ($R^2 = 97.5$) proved that more than 97% of the experimental points were adequate independent variables.

The highest viscosity reading obtained was 127.8 ± 19.4 mPa·s, and the lowest was 44.1 ± 3.1 mPa·s. Among all three factors, xanthan gum had the most significant effect on viscosity. This finding was similar to the results obtained by Mozafari *et al.*, who found that xanthan affected the viscosity of low-fat low-cholesterol mayonnaise [20].

Also, Kumar *et al.* illustrated that xanthan gum significantly impacted the viscosity of egg-free

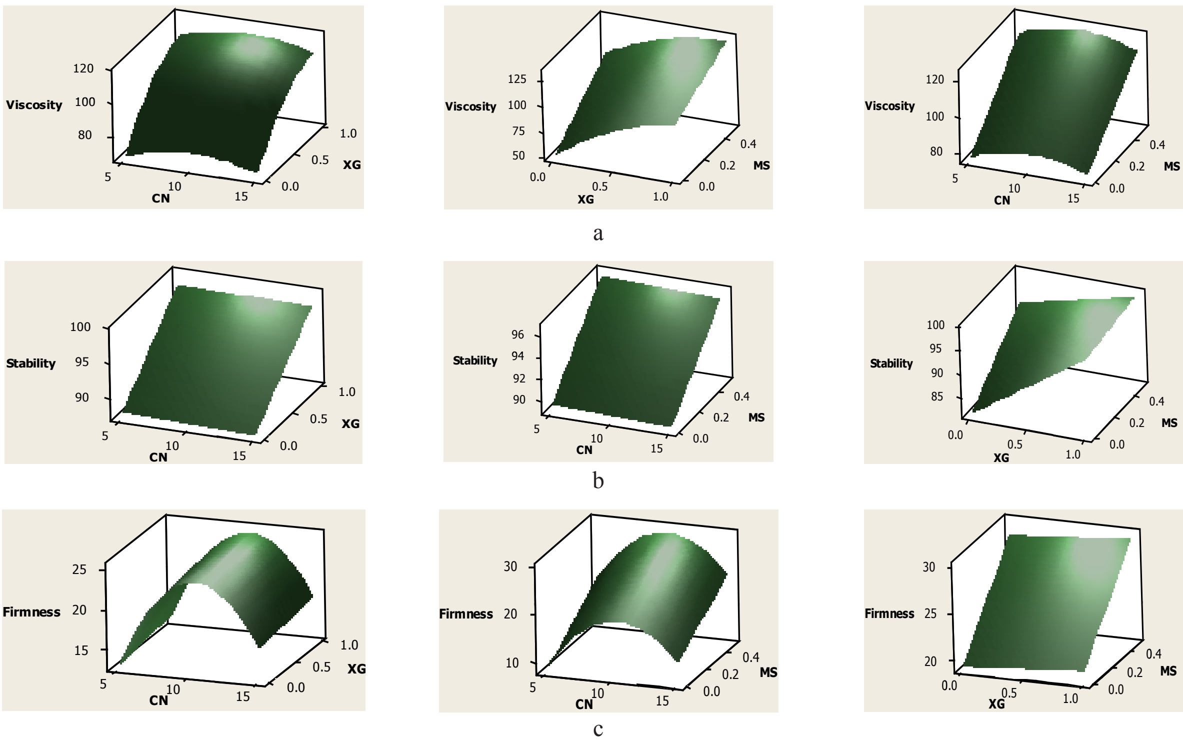

Figure 1 Surface plots of viscosity (a), solubility (b), and firmness (c) changes in low-fat egg-free mayonnaise by formulation parameters

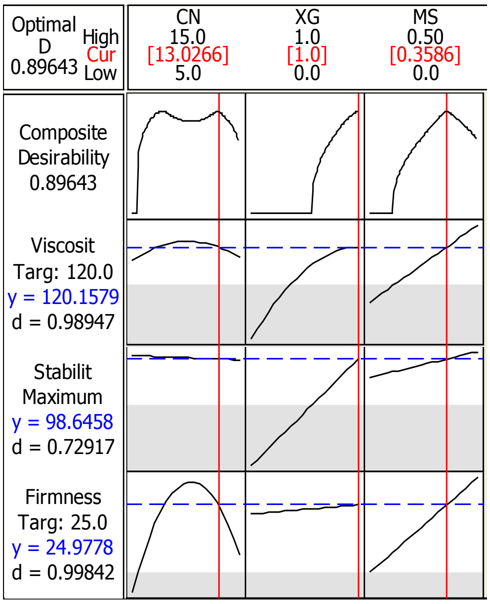

Figure 2 Response optimization

mayonnaise produced by ultrasonication [26]. The experimental outcomes and contour plots showed that a larger amount of xanthan gum followed by modified starch improved the viscosity of mayonnaise samples. For standard oil, the viscosity and flow behavior in water emulsion was captivated by the dispersed phase and controlled by the hydrophilic additives, such as sugar, salt, and polymeric thickener [27].

Effect of independent variables on stability (Y_s). Egg-free virgin coconut oil mayonnaise samples proved moderate to high stability, depending on the emulsifier used in the formulation. The linear effect of cashew nut protein isolates (X_c), xanthan gum (X_x), modified starch (X_m), and a combination of xanthan gum and modified starch ($X_x{\cdot}X_m$) had significant effects on the stability of egg-free virgin coconut oil mayonnaise. The remaining factors proved insignificant (P-value > 0.05) and were removed. A reduced model equation for stability was predicted as below:

$$Y_S = 81.89 - 0.033\,X_c + 15.74\,X_x + 24.42\,X_m - 20.40\,X_x{\cdot}X_m \quad (8)$$

The stability of samples was 100% for formulations 4 and 13, which had the maximal amount of emulsifier. This result was similar to the findings obtained by Mozafari *et al.*, who achieved a good stability of low-fat low-cholesterol mayonnaise with the maximal amount of xanthan gum and Zodo gum as emulsifiers [20]. In this study, the formulations of egg-free virgin coconut oil mayonnaise with xanthan gum and modified starch had higher emulsion stability than the control samples. Lee *et al.* reported similar findings in their study of low-fat mayonnaise with gelatinized rice starch and xanthan gum [24].

Table 5 Optimal values of emulsifiers (factors) derived through response surface methodology

Factor	Optimized value, g	Percentage in formulation, %
Cashew nut protein isolates	13.0	12.6
Xanthan gum	1.0	1.0
Modified starch	0.4	0.4

Two formulations demonstrated a much lower stability, namely formulation 5 (cashew nut protein isolates (X_c) – 5, Xanthan gum (X_x) – 0, Modified starch (X_m) – 0) and formulation 20 (cashew nut protein isolates (X_c) – 15, Xanthan gum (X_x) – 0, Modified starch (X_m) – 0). The stability was 81.8 ± 0.7 and 79.2 ± 0.9%, respectively.

Therefore, cashew nut protein isolates had an almost negligible effect as natural emulsifiers on the stability of the emulsion. In addition, the percentage of virgin coconut oil used in this formulation was approximately only 30–31%. This indicates that emulsion stability was affected by the biopolymers used in the system. According to Lee *et al.*, a lower amount of oil resulted in a significant decline in mayonnaise stability [24]. Therefore, such biopolymers as starches and gums have to be combined with such fat-reduced formulation products as stabilizers.

Effect of independent variables on firmness (Y_f). According to Khor *et al.*, firmness is the product's ability to resist deformation or breaking and increases with the force required for penetration [28]. Higher firmness of emulsion makes it difficult for the mouth to break the sample and swallow. The interactions between proteins and oils in a network structure are known to increase mayonnaise firmness [29].

Based on the P-value, all linear (X_c, X_x, and X_m) and quadratic effects of cashew nut protein isolates ($X_c{\cdot}X_c$) had a significant impact (P < 0.05) on the firmness. The best reduced model equation for predicting firmness was as follows:

$$Y_f = -21.18 + 7.74\,X_c + 0.97\,X_x + 19.10\,X_m - 0.3683\,X_c{\cdot}X_c \quad (9)$$

In this study, fat content in egg-free virgin coconut oil mayonnaise was 30%, which was lower than that in whole fat mayonnaise (70%). Such reduction of fat content caused a lower droplet density, which affected the emulsion stability by weakening the interactions between droplets. However, such lower oil content increased the aqueous phase and decreased the dispersed phase, which reduced the firmness and viscosity of the emulsion [30]. Singla *et al.* reported similar findings: a higher amount of xanthan gum with maltodextrin as thickener increased firmness and stickiness values [31].

Response optimization and model validation. A graphical optimization (Fig. 2) was performed using Minitab 16 package to optimize the percentage of

Table 6 Predicted optimal value and experimental values of response

Response	Experimental value	Predicted value	*P*-value
Viscosity, mPa·s	102.4	120.2	0.1
Stability, %	99.5	98.7	0.1
Firmness, g	21.8	25.0	0.2

* *P*-values < 0.05 are significant differences using Tukey Method test between experimental value and predicted value

Table 7 Proximate analysis and physicochemical properties of optimal formulation of egg-free virgin coconut oil mayonnaise and reference sample

Analysis	Egg-free virgin coconut oil mayonnaise	Reference mayonnaise	*P*-value
Viscosity, mPa·s	102.4 ± 4.1[a]	121.1 ± 16.0[b]	0.2
Stability, %	99.5 ± 0.3[a]	99.7 ± 0.2[a]	0.2
Firmness, g	21.8 ± 1.5[a]	25.3 ± 5.1[a]	0.3
Water activity	1.0 ± 0.0[a]	1.0 ± 0.0[a]	0.0
pH	4.0 ± 0.0[a]	4.0 ± 0.0[b]	0.2
Moisture content, %	34.7 ± 2.9[a]	35.8 ± 4.3[a]	1.0
Ash content, %	3.3 ± 0.5[a]	3.6 ± 1.1[b]	1.0
Protein content, g/100 g	2.6 ± 0.2	1.4*	0.0
Carbohydrate content, g/100 g	14.0 ± 3.7	9.2*	0.1
Fat content, g/100 g	27.5± 3.6	66.2*	0.0

*Values obtained from product nutritional information

emulsifier. The optimal values of emulsifiers were 13.0 g for cashew nut protein isolates, 1.0 g for xanthan gum, and 0.36 g for modified starch (Table 5). The desired response required the highest amount of xanthan gum.

Table 6 illustrates the predicted optimal and experimental values of response, viscosity, stability, and firmness. Based on the two-sample t-test, the *P*-value for all responses was > 0.05. Statistically, there was no significant difference between the experimental and predicted values. Thus, the model and the reduced model equations were validated and accepted.

Proximate analysis and physicochemical properties. Table 7 shows the proximate analysis and physicochemical properties of the optimal formulation of egg-free virgin coconut oil mayonnaise and reference samples. They demonstrated a significant difference ($P < 0.05$) in fat content, protein content, water activity, and consistency. In the egg-free virgin coconut oil mayonnaise, fat content, water activity, and consistency were significantly lower, whereas the protein content was higher compared to the reference product. However, the comparative analysis showed no significant difference in terms of viscosity, stability, firmness, cohesiveness, pH, moisture content, ash content, and carbohydrate content.

Singla *et al.* compared the firmness of the standard and the egg-free mayonnaise samples, and the egg-free mayonnaise showed a higher firmness [31]. However, the high-fat content in the standard mayonnaise caused an increment in textural firmness and stickiness by keeping the neighboring oil droplets flocculated to form a thin gel network.

In this study, thickeners enhanced the firmness and stickiness values in the egg-free virgin coconut oil mayonnaise compared with the egg-containing sample. Generally, the texture of mayonnaise depends on the ingredient selection and the effect of thickening agents used in the system.

The pH of the egg-free virgin coconut oil mayonnaise was acidic, and pH 4 was similar to that of the reference mayonnaise. The acidic emulsion is formed when adding lemon juice or vinegar. Acidic state extends the shelf life of the product and ensures its microbiological stability [28].

Based on [32, 33], mayonnaise producers favor higher acidity because it improves the microbial stability, emulsion stability, and viscoelasticity properties. Moisture content is a significant factor as it affects stability and shelf life. The moisture content in the sample produced by applying the optimal conditions was 34.7 ± 2.9%, while for the commercial sample it was 35.8 ± 4.3%, which indicated no significant differences. This result could be due to the similar content of solid materials used to formulate the egg-free virgin coconut oil mayonnaise. The water activity of the egg-free virgin coconut oil mayonnaise was significantly lower compared to reference sample. Even though the percentage of water was higher in this formulation, a higher amount of emulsifier was expected to bind all the molecules to obtain properties similar to standard mayonnaise.

Ash content was 3.3 ± 0.5% for the egg-free virgin coconut oil mayonnaise and 3.6 ± 1.1% for the commercial sample. The differences between these results might be due to the different ingredients applied for the production.

The protein content of the egg-free virgin coconut oil mayonnaise was 2.6 ± 0.2 g, which was higher than the labeled value of commercial sample (1.4 g). This is primarily because of the protein-based emulsifiers used in the formulation. The carbohydrate content of the egg-free virgin coconut oil mayonnaise was 14.0 ± 3.7 g, which was higher than in the labeled value of commercial sample (9.2 g). This result also could be due to the differences in the formulations.

The fat content of the egg-free virgin coconut oil mayonnaise was 27.5 ± 3.6 g/100 g, whereas for the reference mayonnaise it was 66.2 g/100 g. This result was expected because the experimental low-fat eggless mayonnaise contained 30% of fat, while the commercial sample was a whole-fat mayonnaise. Standard mayonnaise formulation includes 60–80% of fat, depending on the composition and type of oil [33, 34].

Therefore, a lower amount of oil in the formulation resulted in a lower fat content.

CONCLUSION

The research objective was to improve the application of egg replacers in low-fat virgin coconut oil mayonnaise using response surface methodology. The optimal combination of three independent variables was as follows: cashew nut protein isolates – 12.6%, xanthan gum – 1.0%, and modified starch – 0.3%. We produced a high-quality egg-free virgin coconut oil mayonnaise with optimal viscosity, stability, and firmness. The predicted response values under the defined optimal levels were generally in accordance with the model. The proximate analysis and physicochemical properties of the egg-free virgin coconut oil mayonnaise had a lower fat content, water activity, and consistency, as well as a higher protein content compared to the reference sample.

Therefore, a mix of cashew nut protein isolates, xanthan gum, and modified starch at optimal levels could be used as a plant-based substitute to improve the viscosity, texture characteristics, and stability of mayonnaise. More investigations are required to assess the sensory properties and storage stability of the egg-free virgin coconut oil mayonnaise, which could be a good product for vegan consumers.

CONTRIBUTION

Nameer Khairullah Mohammed performed the experiments, drafted the manuscript, and proofread the article. Hemala Ragavan developed the research concept, performed the formal analysis, worked with the software, and drafted the article. Nurul Hawa Ahmad performed the data validation, wrote the review, and edited the manuscript. Anis Shobirin Meor Hussin supervised the project, developed the methodology, and acquired the funding. The manuscript was checked and approved by all the authors. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interests regarding the publication of this article.

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