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Evaluation of techno-functional properties of fava bean aquafaba powder in vegan muffins: Effects of locust bean gum and foam-mat drying

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ABSTRACT

The fava bean aquafaba with and without locus bean gum (LBG) was foam-mat dried at 50 °C, 60 °C, and 70 °C and used as an egg replacer in the vegan muffin. Foams, muffins, and aquafaba powders were characterized using various analyses. The maximum foam overrun (832.37 %) and the minimum foam density (0.1067 g/ml) were observed at fresh aquafaba. As the drying temperature increased, foam capacity increased to 427 %. The addition of LBG to aquafaba and using 70 °C for drying increased foam stability and decreased foam drainage. Baking loss and specific volume of muffins ranged between 15.31 % to 19.06 % and 1.79 ml/g to 2.42 ml/g, respectively. The moisture diffusion coefficient and activation energy were 1.380–5.448× 10^{-9} m^2/s and 33.78–40.93 kJ/mol, respectively. Mathematical modeling showed the suitability of the Middilli & Kucuk model for showing the drying behavior of aquafaba. The powder dried at 70 °C showed the best wettability (0.97 min for non-gum-added aquafaba powder) and produced muffins with the highest volume (135 ml for gum-added aquafaba powder). Adding LBG to aquafaba and foam-mat drying could improve the techno-functional properties of foam as an egg replacer in vegan muffins.

1. Introduction

Eggs are used in many food products to add softness, color, and texture. Eggs show excellent foaming, binding, and emulsifying properties, which are crucial for preparing various foods such as mousses, mayonnaise, cakes, and muffins (Mustafa et al., 2018). Some customers cut down on their egg consumption due to health concerns (cholesterol intake), dietary preferences (veganism), and egg allergies. Thus, identifying egg substitutes has become increasingly important. However, removing eggs from recipes can be challenging, especially since they are crucial for providing structure in products like muffins (Crawford et al., 2024).

Recently, there has been a growing demand for using legume wastewater (Aquafaba) as an egg- replacer. Aquafaba is a viscous liquid obtained from cooked legumes, considered a waste product (Crawford et al., 2023; Yazici et al., 2023). It is a useful component for baking goods as an egg substitute due to its functional properties (such as foaming, emulsifying, gelation, thickening, and binding) (Erem et al., 2023; He et al., 2021). Many authors used aquafaba in the production of cakes and muffins (Aslan & Ertaş, 2020; He et al., 2021; Mustafa et al., 2018; Nguyen et al., 2021). Buhl et al. (2019) discovered that chickpea aquafaba could act as a foaming agent. According to its emulsifying properties, authors demonstrated that the emulsion stability had a direct relation with pH level. Lima et al. (2024) reported that the foam stability of chickpea aquafaba could be improved by increasing the cooking time, decreasing the pH, and adding citric acid and cream tartar. Some authors reported that cakes produced from chickpea aquafaba had flat and slightly collapsed structures with a lower volume index compared with the control sample (Aslan & Ertaş, 2020; Mustafa et al., 2018). The addition of hydrocolloids to aquafaba could stabilize dispersed systems, thus improving the properties of cakes and muffins (Crawford et al., 2024). It was stated that adding hydrocolloids such as xanthan gum (XG) and hydroxypropyl methylcellulose (HPMC) to aquafaba could affect the viscosity, decrease the foam liquid drainage, and increase the foam volumes (Crawford et al., 2023). The same authors reported that the addition of these hydrocolloids to pressure-cooked chickpea aquafaba significantly increased the volume index of cake (Crawford et al., 2024). It was shown that the use of various hydrocolloids such as Locust bean gum (LBG), guar gum, and Arabic gum improved the texture, volume, and porosity of cakes (Salehi, 2020). LBG or carob gum is an anionic polysaccharide, produced by grinding the endosperm of carob pod seeds (Chen et al., 2025). The functional properties of LBG, including

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thickening, stabilizing, and emulsifying, make it an ideal candidate for use in cake formulation (Salehi, 2020). Despite existing research, the impact of LBG on the foaming properties of aquafaba and aquafaba-based muffins remains unexplored.

Aquafaba from Haricot beans, Garbanzo chickpeas, whole green lentils, split yellow peas, kidney beans, black-eyed peas, and chickpeas have been investigated by authors (Buhl et al., 2019; Crawford et al., 2024; Kilicli et al., 2023; Mustafa et al., 2018; Nguyen et al., 2021; Yazici et al., 2023). Fava bean (*Vicia faba* L.) ranks as the seventh most important legume globally, which has drawn more attention recently due to its high protein content (19–39 %) and techno-functional properties such as emulsification, foamability, and gelation. Thus, it can produce stable foam, which can be used in vegan muffin formulations (Herneke et al., 2023). However, there are very few studies about the foaming properties of fava bean aquafaba and its utilization in muffins. According to Ramos-Figueroa et al. (2023), the foaming capacity decreased when foam-inducing components isolated from fava beans (Aquafaba) were treated enzymatically, suggesting that both protein and carbohydrates play a role in foaming capacity. Sharan et al. (2022) investigated the connection between the functional characteristics of fava beans and their protein-associated responses. The authors showed that isoelectric pH was inappropriate for foam stability and that protein acid hydrolysis only enhanced foaming at neutral pH. Kamani et al. (2024) showed how the characteristics of protein powder made from fava beans were affected by dehulling and milling, and the protein from dehulled flour had greater foamability. According to Herneke et al. (2023), the potential of protein nanofibrils derived from fava beans to enhance foam characteristics appeared to be concentration-dependent, since the foams produced at 1 mg/ml were less stable than those formed from the non-fibrillated protein.

An important challenge with aquafaba is its high water content, causing rapid deterioration. Drying by decreasing the moisture content results in a reduction in microbial, physical, and chemical deterioration (Kian-Pour et al., 2024). The foam-mat drying method is a mild drying operation, which first turns a liquid or semiliquid food into stable foam and then dries it. The structure of foam needs to be stable during the drying process; therefore, the addition of a stabilizing agent to the liquid can prevent the foam from collapsing during drying by reducing surface tension between interfaces (Kumar et al., 2023). As foam has a large surface area and a porous structure, switching from liquid food to foam can enhance the drying kinetics, resulting in rapid drying at lower temperatures. Foam mat dry powders provide several advantages, such as enhanced product quality with nutrient preservation, affordability for easily reconstitutable powders, and simplicity of reconstitution (Aslan & Ertaş, 2021).

To the best of our knowledge, the effect of LBG and foam-mat drying on the techno-functional properties of foam, vegan muffins, and dried fava bean aquafaba powder has not yet been evaluated. Thus, the current study aimed at determining the foaming properties of fava bean aquafaba as well as the quality properties of muffins produced from both fresh and dried aquafaba. The drying kinetics and physicochemical properties of foam-mat dried aquafaba powders were examined as well.

2. Materials and methods

2.1. Materials

Commercial dried fava bean, almond milk (Alpro, Belgium, FL), baking powder, vanillin, sugar, flour, and oil were obtained from the local market (Istanbul/ Turkey). LBG (E410) was purchased from an industrial company (Benosen Gıda San. Kim ve Dış Tic. Ltd. Şti).

2.2. Aquafaba production

Aquafaba was prepared according to the method described by Nguyen et al. (2021) with some modifications. Before cooking, dried fava beans were soaked in distilled water at 25 °C for 24 h, then drained and washed twice. The soaked legumes were boiled in a pot at 100 °C for 1 h with a legume/water ratio of 1:1.5. Then, they were cooled to room temperature, and the legumes were removed. Cooking water, named fresh fava bean aquafaba (FB), was kept in the refrigerator (+4 °C) for 12 h. The fresh fava bean aquafaba with gum (FB-G) was prepared by adding 1 % (*w*/w) LBG to the fresh fava bean aquafaba (Crawford et al., 2023).

2.3. Preparation of vegan muffins

A multi-stage mixing procedure modified by Crawford et al. (2024) was used to create the muffin batter. A Kitchen-Aid stand mixer (Sinbo, SMX-2769, Turkey) was used in this study. The stand mixer operated at different speeds. Generally, pastry dough is stirred at speed 1. Speeds 2 and 3 are low and can be used for mixing splashy batters or mashing vegetables. For mixing cookie dough or the initial steps of creating a meringue, medium speed—which refers to speeds 4 and 5—is perfect. At a stand mixer, speeds 6 and 7 are regarded as medium-high speeds. For medium-fast whipping of materials that need the inclusion of air, egg whites, and foams, this is the ideal speed. First, in the Kitchen-Aid stand mixer 95 ml of FB or FB-G was whipped for 30 min at speed 6 using a wire whip attachment to produce foam. Then, 240 g of sugar was added to the foam and whipped for 3 min. After that, 200 ml of almond milk and 180 ml of oil were added while whipping for 2 more min. Then, 260 g sifted flour, 5 g vanillin, and 10 g baking powder were added and whipped for 2 min. Following that, 70 g of the prepared batter was weighed by the precision scale (±0.001) (Vibra, AJ-320 CE, Japan) and transferred to the muffin mold. Batters were baked at 180 °C for 40 min in the oven (Vestel, AF-8785, Turkey) and were cooled on a wire rack at room temperature before analysis. Control cake was produced by replacing 95 ml liquid whole egg (WE) instead of the aquafaba.

2.4. Production of Aquafaba powder by foam-mat drying

Fresh FB and FB-G were whipped separately by the Kitchen-Aid stand mixer at speed 6 for 30 min. Then, the foam was spread on a petri dish at a thickness of 10 mm. Foam-mat drying was carried out at 50 °C, 60 °C, and 70 °C in a tray dryer (Termal, G11420SD, Turkey) to reach a constant moisture content (Aslan & Ertaş, 2021). The dried foams were scraped, milled with a kitchen grinder (Sinbo, SCM 2934, Turkey), packaged, and stored at 4 °C until analysis (Izadi et al., 2020; Nunes et al., 2022). For evaluation of the foaming and muffin properties of dried aquafaba powder, first, the dried powders were dissolved in distilled water to produce liquid aquafaba and then exposed to different analyses.

2.5. Determination of foam properties

2.5.1. Foam overrun

Foam overrun was measured as described by Kanha et al. (2022). The weight of 100 ml liquids aquafaba (m_1) was measured with the precision balance (±0.001) (Vibra, AJ-320 CE, Japan). The liquid aquafaba was whipped by the Kitchen-Aid stand mixer at a speed of 6 for 30 min to produce foam. Then, 100 ml of foam was placed in a graduated cylinder and its weight was measured (m_2). Three repetitions were made for this analysis. The foam overrun value was determined using Eq. (1) (Crawford et al., 2023; Kanha et al., 2022):

$$\textit{Foam overrun}\ (\%) = \left(\frac{m_1 - m_2}{m_2}\right) \times 100 \tag{1}$$

2.5.2. Foam density

Foam density was evaluated according to Aslan and Ertaş (2021) with some modifications. The weight of 100 ml aquafaba foam (m_2) was used for the determination of foam density by Eq. (2) (Kanha et al., 2022):

$$Foam\ dnesity\ (g/ml) = \frac{m_2}{V} \tag{2}$$

2.5.3. Foaming capacity and stability

The foaming capacity of the sample was determined according to Crawford et al. (2023) with some modifications. Briefly, 30 ml of liquid aquafaba (V_i) was whipped with the mechanical homogenizer (Dlab, OS20-S, China) at 2200 rpm for 20 min to produce foam. The volumes of the foams were measured at 0 min (V_0) and 30 min (V_{30}) after they were transferred to 250 ml graduated cylinders. Foaming capacity and foaming stability were calculated using Eq. (3), and Eq. (4), respectively.

$$Foaming\ capacity\ (\%) = \frac{V_0}{V_i} \times 100 \tag{3}$$

$$Foaming\ stability\ (\%) = \frac{V_{30}}{V_i} \times 100 \tag{4}$$

Furthermore, the volume of foam (V_t) after 15, 30, 60, and 90 min were used to evaluate the change in the foam stability during the time using Eq. (5):

$$Foaming\ stability\ at\ different\ time\ (\%) = \frac{V_t}{V_i} \times 100 \tag{5}$$

2.5.4. Foam liquid drainage

To determine the foam liquid drainage, 60 ml liquid aquafaba was whipped by the Kitchen-Aid stand mixer at a speed of 6 for 30 min to produce foam. Then, the produced foam was transferred to the 120 ml funnel, set on the top of 150 ml graduated cylinders. A gauze was placed inside the funnel to help retain the foam. The volume of dripping liquid from foam was measured after 0, 1, and 2 h and reported as the drainage volume of foam (ml) (Crawford et al., 2023).

2.6. Characterization of vegan muffins

2.6.1. Baking loss

The baking loss was determined by measuring the weight of the batter (W_0) before baking and the weight of the baked muffin (W_1) after cooling to room temperature by the Eq. (6) (Crawford et al., 2024; Yazici et al., 2023).

$$Baking\ loss\ (\%) = \left[\frac{(W_0 - W_1)}{W_0}\right] \times 100 \tag{6}$$

2.6.2. Volume and specific volume of muffin

The volume of muffins (ml) was evaluated using the rapeseed displacement method. Specific volume was calculated by dividing the volume of the muffin by its weight (ml/g) (Yazici et al., 2023).

2.6.3. Volume index

The baked cooled muffins were cut vertically into two equal pieces from the middle. The volume index was calculated using the height of each slice's face measured at various points with a digital caliper (Eq. 7) (Mustafa et al., 2018).

$$Volume\ index = B + C + D \tag{7}$$

where C represents the cake's center height and B and D represent the muffin sample's heights at 1.5 cm from the center at the left and right sides, respectively.

2.6.4. pH analysis

The pH value has a direct effect on the volume, texture, and pore structure of cakes. The method described by Mustafa et al. (2018) was used to measure the pH of muffins. Briefly, 10 g of ground muffin was added to 90 ml of distilled water, mixed with a homogenizer for 1 min, and kept at 4 °C for 1 h. Then, the pH of the supernatant was measured by a digital pH meter (Mettler Toledo, FP20, Switzerland).

2.7. Foam- mat drying

2.7.1. Kinetics of drying

Experimental data was used to determine the drying rate (*DR*) (Eq. 8) and moisture ratio (*MR*) of samples (Eq. 9).

$$DR = \frac{M_{t2} - M_{t1}}{t_2 - t_1} \tag{8}$$

$$MR = \frac{\overline{M} - M_e}{M_0 - M_e} \tag{9}$$

where, DR, M_{t2}, and M_{t1} represent the drying rate (kg water/kg dry solid. min), and moisture content (kg water/kg dry solid) of aquafaba at the drying time of t_2 and, respectively. Also, $\overline{M}$, M_e, and M_0 are the average, equilibrium, and initial moisture content (kg water/kg dry solid) of the sample, respectively (Kian-Pour, 2023).

2.7.2. Mathematical modeling

The Levenberg-Marquardt algorithm was used in a nonlinear regression analysis to match the drying curves to the Newton (Eq. 10), Wang & Sing (Eq. 11), and Middilli & Kucuk (Eq. 12) drying models by the software package (SPSS statistics 23, IBM. 2015, USA).

$$MR = Exp\ (-kt) \tag{10}$$

$$MR = 1 + at + bt^2 \tag{11}$$

$$MR = aexp(-kt^n) + bt \tag{12}$$

The goodness of fit was evaluated according to the statistical criteria of determination coefficient (R^2) (Eq. 13), root mean square error (*RMSE*) (Eq. 14), and reduced chi-square (x^2) (Eq. 15).

$$R^2 = 1 - \left[\frac{\left(\sum_{i=1}^{N} MR_{pre,i} - MR_{exp,i}\right)^2}{\left(\sum_{i=1}^{N} \overline{MR}_{pre,i} - MR_{exp,i}\right)^2}\right] \tag{13}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N}} \tag{14}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - n} \tag{15}$$

where $MR_{exp,i}$, $MR_{pre,i}$, N, and n are the experimental and predicted moisture ratios, number of observations, and number of model constants, respectively (Kian-Pour, 2023).

2.7.3. Effective moisture diffusion coefficient (D_{eff}) and activation energy (Ea)

Fick's second law of diffusion was used to evaluate D_{eff} for infinite slab geometry by linear regression analyses (Eq. 16) (Paula et al., 2020).

$$MR = \frac{8}{\pi^2} \sum_{0}^{\infty} \frac{1}{(2n+1)^2} exp\left\{-\frac{(2n+1)^2}{4}\ \frac{\pi^2 D_{eff} t}{x_1{}^2}\right\} \tag{16}$$

where D_{eff}, n, t, and x_1 represent the effective diffusion coefficient (m/s^2), the number of terms in the summation, drying time (s), and the half thickness of the foam (m), respectively.

The temperature dependence of D_{eff} was represented by E_a. The Arrhenius equation was used to evaluate the E_a by the Eq. (17).

$$D_{eff} = D_0 exp\left(\frac{-E_a}{RT}\right) \quad (17)$$

where, E_a, D_0, R and T are activation energy (kJ/mol), the pre-exponential factor (m^2/s), the universal gas constant (kJ/mol K), and temperature (K), respectively (Izadi et al., 2020).

2.8. Characterization of Aquafaba powder

2.8.1. Bulk, tapped and particle densities

The method described by Aslan and Ertaş (2021) was used to determine the bulk and tapped densities. For bulk density first, the empty weight of a 10 ml measuring cylinder was recorded. Then, the cylinder was filled with aquafaba powder without being tapped and the mass of the powder was calculated (Eq.18). After manually tapping the cylinder 100 times, the volume was used to calculate the tapped density. The tapped density was determined using the final volume (Eq.19).

$$Bulk\ density = \frac{Weight\ of\ powder\ (g)}{Volume\ of\ powder\ (ml)} \quad (18)$$

$$Tapped\ density = \frac{Weight\ of\ powder\ (g)}{Final\ volume\ of\ tapped\ powder\ (ml)} \quad (19)$$

The particle density of the aquafaba powders was determined according to the method developed by Aslan and Ertaş (2021). Briefly, 1 g aquafaba powder was transferred to the 10 ml measuring cylinder. Five milliliters of petroleum ether were added, and the measuring cylinder was shaken to get the powder particles suspended. Then, 1 ml of petroleum ether was used to rinse away all of the powder particles adhering to the cylinder wall, and the entire volume of petroleum ether with suspended particles was measured (Eq. 20).

$$Particle\ density = \frac{Weight\ of\ powder\ (g)}{Total\ volume\ of\ petroleum\ ether\ with\ suspended\ powder\ (ml) - 6} \quad (20)$$

2.8.2. Porosity, Flowability, cohesiveness and wettability

The bulk, tapped and particle densities of aquafaba powder were used for the determination of porosity (Eq. 21), flowability (Carr index) (Eq. 22), and cohesiveness (Hausner ratio) (Eq. 23) (Aslan & Ertaş, 2021).

$$Porosity = \left(\frac{\rho_{particle} - \rho_{tapped}}{\rho_{particle}}\right) \times 100 \quad (21)$$

$$Carr\ index = \left(\frac{\rho_{tapped} - \rho_{bulk}}{\rho_{tapped}}\right) \quad (22)$$

$$Hausner\ ratio = \left(\frac{\rho_{tapped}}{\rho_{bulk}}\right) \quad (23)$$

The time needed to wet every particle in powder samples is known as the wettability time. The wettability of samples was measured according to the method described by Aslan and Ertaş (2021). Briefly, a 100 ml beaker was filled with 50 ml of distilled water at 25 °C. When the 0.5 g powder samples were put onto the surface water, the timer started. The time needed to moisten every particle was reported as the wettability of aquafaba powder.

2.9. Statistical analysis

The experimental results were subjected to a variance analysis (ANOVA) with Tukey's tests using the software package (SPSS statistics 23, IBM. 2015, USA), and the significant level was considered as $p < 0.05$.

3. Results and discussion

3.1. Characterization of Aquafaba foam

3.1.1. Foam overrun

The ability of a liquid to add air to produce foam is measured by foam overrun (Donatus et al., 2020). The foam overrun values of aquafaba samples ranged from 458.32 % to 832.37 % (Table 1). The maximum foam overrun was observed at fresh FB samples, not significantly ($P >$ 0.05) different from the WE. The foam overrun of WE was 781.05 % in our study, higher than that of egg white reported in the literature at 225 % and 505.05 % (Crawford et al., 2023; Dabestani & Yeganehzad, 2019), attributable to the differences in the composition of WE and egg white as well as foam preparation conditions. Our results are in good agreement with the previous study, reporting that foam overrun values of canned pulses were in the range of 200 % to 1466 % (Donatus et al., 2020). Foam-mat drying significantly ($p < 0.05$) decreased the foam overrun values of fava bean aquafaba powders compared with fresh FB. Protein denaturation and some interactions between protein molecules would occur because of the thermal treatment of aquafaba samples. Some hydrophobic groups may embedded in these interactions, and as molecule size increases, molecular mobility would likewise decrease. The reduction in foam overrun qualities is a consequence of these interactions (Dabestani & Yeganehzad, 2019). The addition of 1 % LBG significantly ($P < 0.05$) decreased the foam overrun of fresh FB-G (458.32 %) compared with fresh FB (832.37 %) samples. The addition of LBG to the aquafaba can increase the viscosity of samples. Liquid with higher viscosity exhibits resistance against shearing force during the whipping, preventing air incorporation in the foam structure and resulting in less foam overrun (Dabestani & Yeganehzad, 2019). Additionally, it limits the mobility of surface-active molecules adsorbed at the interface between air and water. It delays the lamella thinning stage and prevents gas diffusion to the lamella or other bubbles. Reduced surface and interfacial tension due to the addition of gum may also be the cause of decreases in foam overrun (Dabestani & Yeganehzad, 2019; Kanha et al., 2022). It was stated that the addition of 0.2 % HPMC or XG to chickpea aquafaba decreased the foam overrun of samples to 391 % and 351 % compared with the control (409 %) sample, respectively (Crawford et al., 2023). The foam overrun values of dried aquafaba without gum significantly ($P < 0.05$) decreased compared with fresh FB aquafaba. However, a slight increase was observed in the foam overrun values of dried aquafaba with gum compared with fresh FB-G samples. Protein concentration in the liquid phase had to be high enough to promote volume expansion and enhance the formation of new water-air interfaces over time (Begliyev et al., 2024). The addition of LBG with an increase in the protein content of samples can improve the foam overrun properties. Among dried aquafaba, the maximum percentage of foam overrun (689.32 %) was observed in the fava bean aquafaba powder dried at 70 °C (FBP-70) samples.

3.1.2. Foam density

The expansion of foam can be measured using its density. The minimum foam density was observed at fresh FB, not significantly ($p > 0.05$) different from that of the WE samples (Table 1). Drying increased the foam density of aquafaba without gum compared with FB. FBP-70

Table 1
Foaming properties of fava bean aquafaba.

Sample	Foam overrun (%)	Foam (g/ml) density	Foaming Capacity (%)	Foam Stability (%)	Foam Drainage volume (ml) after 1 h	Foam drainage volume (ml) after 2 h
WE	781.05 ± 43.73^{cd}	0.1154 ± 0.0044^{a}	365.56 ± 18.36^{d}	341.11 ± 25.46^{d}	0.00 ± 0.00^{a}	3.67 ± 0.58^{a}
FB	832.37 ± 50.79^{d}	0.1067 ± 0.0057^{a}	337.78 ± 7.70^{d}	280.00 ± 24.04^{bc}	29.00 ± 1.73^{d}	37.00 ± 1.00^{de}
FBP-50	573.38 ± 13.81^{b}	0.1429 ± 0.0069^{bc}	232.22 ± 5.09^{a}	201.11 ± 1.92^{a}	35.00 ± 2.00^{e}	43.00 ± 1.73^{f}
FBP-60	521.54 ± 49.75^{ab}	0.1564 ± 0.0152^{cd}	272.22 ± 6.94^{bc}	224.44 ± 21.43^{a}	29.67 ± 2.08^{d}	40.67 ± 2.08^{ef}
FBP-70	689.32 ± 45.28^{c}	0.1265 ± 0.0056^{ab}	427.78 ± 20.09^{e}	375.56 ± 13.88^{d}	18.33 ± 1.53^{c}	28.00 ± 2.00^{c}
FB-G	458.32 ± 23.71^{a}	0.1806 ± 0.0084^{c}	291.11 ± 7.70^{c}	291.11 ± 7.70^{c}	23.33 ± 1.16^{c}	33.67 ± 1.53^{cd}
FBP-G-50	472.72 ± 21.80^{ab}	0.1679 ± 0.0049^{de}	242.22 ± 6.94^{ab}	231.11 ± 7.70^{a}	30.67 ± 3.06^{de}	36.00 ± 3.00^{de}
FBP-G-60	556.74 ± 10.75^{ab}	0.1509 ± 0.0022^{cd}	253.33 ± 6.67^{ab}	245.56 ± 5.09^{ab}	28.67 ± 2.08^{d}	35.00 ± 3.61^{de}
FBP-G-70	506.04 ± 38.47^{ab}	0.1654 ± 0.0122^{cde}	288.89 ± 10.18^{c}	284.44 ± 13.88^{bc}	11.00 ± 1.00^{b}	13.00 ± 1.00^{b}

WE: Whole egg, FB: Fresh fava bean aquafaba, FBP-50: Fava bean aquafaba powder dried at 50 °C, FBP-60: Fava bean aquafaba powder dried at 60 °C, FBP-70: Fava bean aquafaba powder dried at 70 °C, FB-G: Fresh fava bean aquafaba with gum, FBP-G-50: Fava bean aquafaba powder with gum dried at 50 °C, FBP-G-60: Fava bean aquafaba powder with gum dried at 60 °C, FBP-G-70: Fava bean aquafaba powder with gum dried at 70 °C. Mean ± standard deviation is computed from Triplicate samples. Different letters in the same column indicate differences significant at $p < 0.05$.

(0.1265 g/ml) showed the minimum foam density, not significantly different ($p > 0.05$) from that of fresh WE and fresh FB. A drying temperature of 70 °C can be chosen for the production of aquafaba powder without gum with low density. Since low-density foams offer a greater surface area, they can aid in accelerating the process of water removal during the baking of cupcakes (Nunes et al., 2022). The addition of LBG to samples significantly increased the foam density of fresh FB-G compared with fresh FB samples. The incorporation of gum into aquafaba can increase the viscosity, preventing air from being trapped during whipping, as a result of which, the foam gets denser or expands less. Besides, increasing the solid content and mass of LBG-added samples results in increasing foam density. Our results are in agreement with other studies. Edleman and Hall (2023) reported that both the viscosity and density of samples increased noticeably when the solid percentage of chickpea aquafaba was raised from 4 % to 13 %. It was stated that increases in the level of protein and sugar in the aquafaba caused increases in viscosity and density. Drying the gum-added aquafaba sample decreased the foam density. Foam-mat drying at 60 °C can produce foam with the minimum foam density among the LGB-added samples. Increasing the amount of air incorporated during mixing causes decreases in the foam density. The higher the air content in the foam, the higher the whip-ability. Less dense foam indicates that more air was trapped within it, increasing the quantity of foam expansion (Bag et al., 2011).

3.1.3. Foaming capacity and stability

The ability of a substance to produce and maintain a foam is known as its foaming capacity. The differences between the foaming capacity of fresh FB aquafaba with WE were not significant ($p > 0.05$), confirming the suitability of fava bean aquafaba as an egg replacer in muffins (Table 1). FB in the present study had approximately the same foaming capacity, as reported in the study by Herneke et al. (2023). Drying at 50 °C and 60 °C decreased the foaming capacity, while interestingly foam-mat drying at 70 °C increased the foaming capacity of FBP-70 samples. The addition of LBG decreased the foaming capacity of fresh FB-G samples, probably related to the increases in the viscosity. In addition, drying LBG-added samples decreased the foaming capacity of samples; however, drying at 70 °C not significantly affect the foaming capacity of fava bean aquafaba powder with gum dried at 70 °C (FBP-G-70) compared with FB-G samples. The consistency and appearance of foods are impacted by their foaming capacity. The amount of interfacial area that can be produced by whipping a protein is a measure of its foaming capacity. In our study, the foaming capacity of aquafaba varied from 232.22 % to 427.78 %, in agreement with other studies. It was stated that the FC of aquafaba from different legumes ranged from 39 % to 725 % (Stasiak et al., 2023). Aslan and Ertaş (2020) studied the possibility of replacing whole eggs with chickpea aquafaba in the formulation of cake. The foaming capacity of the sample with the 0–25–50-75-100 % ratios of aquafaba/egg was found to be 200.00, 253.33, 246.67, 186.67, and 126.67 %, respectively. Alsalman et al. (2020) showed that the foaming capacity of chickpea aquafaba varied from 40.1 to 290.1 %, likely related to the differences in the ratio of legume/cooking water as well as cooking time. Aquafaba needs to be whipped for at least 5 min to have the same foaming capacity as egg white. In addition, external factors such as pressure, temperature, and cooking time can affect the composition and properties of aquafaba (He et al., 2021). Long-term drying of fresh aquafaba at 50 °Cand 60 °C with damage to the quality and structure of protein may be the reason for decreasing the foaming capacity of our samples. Fast drying of samples at 70 °C can produce dried aquafaba with good foaming capacity. According to the results, 70 °C can be chosen as the suitable temperature for the production of dried aquafaba powder.

The foam stability of samples are presented in Table 1. The foam stability of the WE sample was significantly ($p < 0.05$) higher than that of fresh FB, and FB-G samples. As the drying temperature increased, the foam stability increased. FBP-70 showed the highest percentage of foam stability among all aquafaba samples, translated to the lowest degree of liquid separation. It can related to the faster drying of samples at 70 °C compared with other temperatures. The addition of LBG to aquafaba caused an increase in the foam stability of fresh FB-G compared with fresh FB. However, among the LGB-added samples, the lowest foam stability belonged to the samples dried at 50 °C, probably due to the longer drying time/insufficient drying temperature compared with other drying conditions, harming the stability of the sample. Foam stability is a way to measure how rapidly liquid drains from foam and reflects the ability to bind water. It is essential for foam-mat drying and cooking of muffins since it keeps the foam's open structure (Bag et al., 2011). Processing techniques and technological factors will affect the surface characteristics and physical structure of the dried aquafaba (Alsalman & Ramaswamy, 2021; He et al., 2021). Foam with a stable structure is perfect for the production of high-quality food.

The stability of foams reconstituted from dried aquafaba powders continuously decreased at the first 30 min and remained nearly constant for the next 60 min. Among all dried samples, FBP-70 with the highest stability showed good potential for the preparation of muffins. The stability of foam is affected by several factors related to its physiochemical characteristics, such as surface tension, surface viscosity, and elasticity (Bag et al., 2011). Furthermore, the composition of aquafaba such as protein, carbohydrate, and oil contents has an important effect on the foam stability. Proteins have an important role in the stabilization of foams. Proteins' surface viscoelastic characteristics can lower the rates of liquid drainage in the foam lamellae, hence increasing foam stability. The composition of aquafaba should include elements that interact with the bubble surface to produce stable foam. Our results are in agreement with another study that showed the foam stability of kidney beans, chickpeas, haricot beans, and blacked-eyed peas decreased during the time compared with whole egg (Yazici et al., 2023). The foam stability of LGB-added aquafaba samples remained nearly constant until the end of 90 min, confirming the benefit of using LGB for producing more stable foam in the case of muffin production.

The findings of the current study align with those of previous research. Shim et al. (2021) stated that the foam stability of aquafaba from soybean samples was higher than that of chickpeas. Some authors reported that the foam stability of soybean aquafaba was not significantly affected by preparation conditions such as cooking and pre-soaking treatment. Choya et al. (2023) used water, vegetable broth, and meat broth for preparing chickpea aquafaba. They reported that the maximum foam stability was observed at canned aquafaba followed by water, vegetable broth, and meat broth respectively. It was stated that the fat content of the dispersion was most likely a contributing factor in the beef broth aquafaba foam's low stability. When fat and proteins compete for adsorption at the air-water interface, interfacial films with low viscoelastic and steric stability are formed. The highest foam stability of canned aquafaba can be related to the presence of complex polysaccharides as well as the type of process. During the preparation of canned aquafaba, samples were exposed to more intense heat treatments, along with using less water in comparison with normal convectional cooking. It might quicken the solubilization and diffusion of pectins into the aquafaba, and accelerate the starch gelatinization process, increasing the viscosity and stabilizing the foam's three-dimensional structure.

3.1.4. Foam liquid drainage

Foam drainage values of all aquafaba samples significantly ($p < 0.05$) were higher than that of WE samples (Table 1). The addition of gum had a positive effect on the reduction of foam drainage. As the drying temperature increased, the foam drainage decreased. These results are in the same trend as our findings on foam stability. Foam drainage of fresh FB-G samples was lower than that of fresh FB, showing that the addition of gum can produce more stable foam with a lower amount of drainage. LBG via water binding can increase the viscosity of the continuous phase, thus decreasing the liquid drainage from foam (Crawford et al., 2023).To improve the drying properties of food materials, drying needs to be done very quickly. The rapid drying of aquafaba at 70 °C compared with 50 °Cand 60 °C can prevent the collapsing of foam structure during drying, capable of producing foam with higher stability. The addition of LBG to aquafaba can decrease the foam drainage and produce more stable foam. Our results are in good agreement with other studies. Crawford et al. (2023) reported that the addition of XG or HPMC to aquafaba significantly decreased the foam drainage of samples. Even though air is added during the foaming process, a stable network that can hold air bubbles in the foam systems is the only way to achieve aeration (Donatus et al., 2020). Enhancing the stability of aquafaba foam and reducing its drainage are important considerations for market use. The two tactics that can be used to prevent drainage and extend the use of aquafaba foams in the food business

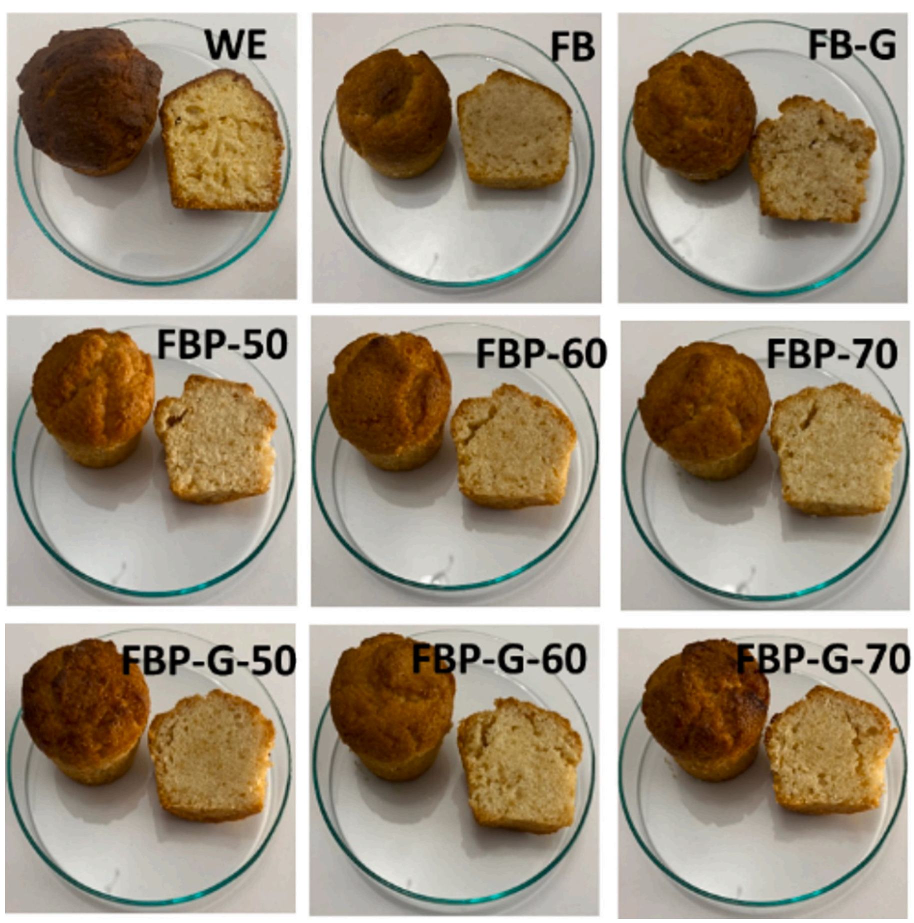

Fig. 1. Vegan muffins prepared from fava bean aquafaba. WE: Whole egg, FB: Fresh fava bean aquafaba, FBP-50: Fava bean aquafaba powder dried at 50 °C, FBP-60: Fava bean aquafaba powder dried at 60 °C, FBP-70: Fava bean aquafaba powder dried at 70 °C, FB-G: Fresh fava bean aquafaba with gum, FBP-G-50: Fava bean aquafaba powder with gum dried at 50 °C, FBP-G-60: Fava bean aquafaba powder with gum dried at 60 °C, FBP-G-70: Fava bean aquafaba powder with gum dried at 70 °C.

Table 2
Characterization of aquafaba vegan muffins.

Sample	Baking loss (%)	Cake volume (ml)	Specific volume (ml /g)	Volume index (cm)	pH
WE	19.42 ± 0.21^{e}	206.67 ± 4.16^{g}	3.22 ± 0.09^{d}	16.60 ± 0.26^{d}	7.42 ± 0.15^{a}
FB	19.06 ± 0.52^{e}	113.3 ± 5.78^{ab}	1.93 ± 0.12^{ab}	15.32 ± 0.11^{b}	9.10 ± 0.07^{b}
FBP-50	18.85 ± 0.50^{e}	101.67 ± 5.86^{a}	1.79 ± 0.11^{a}	13.72 ± 0.12^{a}	7.55 ± 0.30^{a}
FBP-60	18.04 ± 0.09^{cde}	108.00 ± 8.19^{ab}	1.88 ± 0.14^{ab}	14.06 ± 0.41^{a}	7.59 ± 0.16^{a}
FBP-70	16.37 ± 0.29^{abc}	116.00 ± 4.00^{b}	1.98 ± 0.07^{ab}	15.38 ± 0.47^{b}	7.85 ± 0.06^{a}
FB-G	15.31 ± 1.32^{a}	147.33 ± 3.06^{d}	2.40 ± 0.07^{c}	16.31 ± 0.15^{d}	9.05 ± 0.19^{b}
FBP-G-50	15.60 ± 0.57^{ab}	121.33 ± 2.52^{bc}	2.08 ± 0.04^{b}	15.49 ± 0.32^{bc}	7.69 ± 0.40^{a}
FBP-G-60	17.13 ± 0.57^{bcd}	134.67 ± 4.04^{cd}	2.36 ± 0.06^{c}	15.65 ± 0.32^{bc}	7.72 ± 0.08^{a}
FBP-G-70	18.72 ± 0.30^{de}	135.00 ± 4.36^{cd}	2.42 ± 0.09^{c}	15.92 ± 0.18^{bcd}	7.70 ± 0.22^{a}

WE: Whole egg, FB: Fresh fava bean aquafaba, FBP-50: Fava bean aquafaba powder dried at 50 °C, FBP-60: Fava bean aquafaba powder dried at 60 °C, FBP-70: Fava bean aquafaba powder dried at 70 °C, FB-G: Fresh fava bean aquafaba with gum, FBP-G-50: Fava bean aquafaba powder with gum dried at 50 °C, FBP-G-60: Fava bean aquafaba powder with gum dried at 60 °C, FBP-G-70: Fava bean aquafaba powder with gum dried at 70 °C. Mean ± standard deviation is computed from Triplicate samples. Different letters in the same column indicate differences significant at $p < 0.05$.

are additives and processing. In our study, both the addition of gum and drying at 70 °C significantly decreased the foam drainage value.

3.2. Characterization of vegan muffins

3.2.1. Baking loss

Fig. 1 shows the vegan muffin prepared from fava bean aquafaba. Baking loss of samples ranged from 15.31 % to 19.42 % (Table 2). The differences between the baking loss of FB and WE were not significant ($p > 0.05$). Foam-mat drying of non-gum-added samples reduced the baking loss of samples, with the maximum decrease being observed at FBP-70 samples. The addition of gum to the aquafaba significantly decreased the baking loss of FB-G compared with WE and FB samples. It could be related to the water-binding capacity of LBG, preventing free water from evaporating and weight loss in muffins. However, drying gum-added samples caused an increase in the baking loss which was maximum at FBP-50 samples. Baking loss (cooking loss/weight loss) is the amount of weight due to the removal of moisture and other volatiles during baking. Remarkably, cakes with very high and very low baking loss values would normally be quite dry and moist, respectively. The presence of some ingredients with high water binding capacity, which can decrease the water evaporation during baking of muffin, can decrease the baking loss in samples. Our results are in good agreement with other studies. Yazici et al. (2023) reported that in gluten-free cakes, baking loss of Haricoat bean (14.52 %) and kidney bean (13.95 %) cakes were lower than that of control (14.83 %) samples, while for chickpeas (15.53 %) and blacked-eye peas (15.74 %), baking loss was higher. Herranz et al. (2016) showed that the addition of XG to the formulation of the muffin caused a significant decrease in the baking loss of samples.

3.2.2. Volume and specific volume of muffin

The volume of muffins ranged from 101.67 to 147.33 ml, with the maximum at FB-G muffins (Table 2). The volume of all vegan muffins was lower than that of WE muffins. Foam-mat drying of aquafaba without LBG at 70 °C increased the volume of the muffin. It is in the same trend as our finding about higher foam capacity and lower foam density of FBP-70 samples. The addition of LBG to aquafaba significantly ($p < 0.05$) increased the volume of muffins in the samples. Among all muffins produced from dried powder, the minimum volume of muffins was observed in samples dried at 50 °C. Foam-mat drying at 50 °C takes a longer time in comparison with other temperatures. It is in agreement with our results about the lower foam capacity and foam stability of these samples compared with samples dried at 60 °C and 70 °C. In our study, the addition of LBG to aquafaba by increasing the viscosity and stability of the batter caused increases in the volume of the muffin. This is achieved by delaying the settling of starch granules, limiting migration, and loss of air cells before the batter sets (Herranz et al., 2016). Generally, increases in the volume lead to the production of muffins with large pores while samples with a lower volume result in firmer muffins as well as pores with smaller sizes. Both the amount of air incorporated in the batter and gas retention capacity due to the pore structure during baking determine the volume of the cake (Aslan & Ertaş, 2020).

Specific volume is one of the crucial physical characteristics greatly affecting customer acceptability (Bursa et al., 2022). The muffins were evaluated according to their specific volume (Table 2) which ranged from 1.79 ml /g to 3.22 ml /g. The addition of LBG to aquafaba significantly increased the specific volume of FB-G compared with FB samples. As the drying temperature increased, specific volume values of both non-gum-added and gum-added muffins increased. Among all vegan muffins, foams dried at 70 °C produced muffins with higher specific volume compared with foams dried at other temperatures. In general, FBP-G-70 yields muffins with the highest volume per unit weight (which means higher specific volume), which would have significant economic implications. Yazici et al. (2023) reported that specific volumes of gluten-free cake produced from kidney beans, haricot beans, blacked-eye peas, and chickpea aquafaba were 1.7 ml/g, 1.79 ml/g, 1.85 ml/g, and 1.95 ml/g, respectively, significantly lower than that of the control sample (2.54 ml /g).

3.2.3. Volume index

The volume index of samples ranged from 13.72 to 16.60 cm (Table 2). The volume index value of the FB-G sample was significantly ($p < 0.05$) higher than that of FB samples, confirming the positive effect of adding LBG to aquafaba on the muffin properties. Besides, there were no significant differences ($p > 0.05$) between the volume index values of FB-G and WE muffins. As the drying temperature increased, the volume index value of all vegan muffins increased. For both gum-added and gum-non-added samples, using 50 °C dry air produced the muffins with the minimum volume index. This is in agreement with our finding about the low foam capacity and foam stability of dried aquafaba powders at this temperature. In addition, these trends agreed with our findings about the volume and the specific volume of muffins. Therefore, the best temperature for drying aquafaba can be considered as 70 °C. The low volume index of non-gum-added samples can be related to the collapse of cakes' interior foam structure during baking (before they reach the necessary temperature for protein denaturation). The addition of gum to increase the stability of aquafaba foam can produce muffins with a higher volume index (Yazici et al., 2023). Aslan and Ertaş (2020) showed the volume index values of cake at the different concentrations of aquafaba 0 %, 25 %, 50 %, 75 %, and 100 % were 16.9, 16.5, 15.8, 13.0, and 12.8 cm, respectively. Yazici et al. (2023) reported that the volume indexes of gluten-free cakes prepared from kidney beans, chickpeas, haricot beans, and blacked-eye pea aquafaba were 8.95 cm, 10.31 cm, 9.34 cm, and 9.81 cm respectively, which were lower than the control sample (12.8 cm).

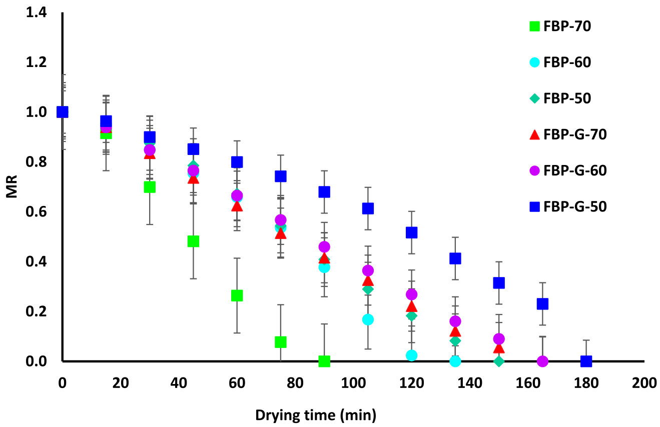

Fig. 2. Variation in the moisture ratio of aquafaba during drying. FBP-70: Fava bean aquafaba powder dried at 70 °C, FBP-60: Fava bean aquafaba powder dried at 60 °C, FBP-50: Fava bean aquafaba powder dried at 50 °C, FBP-G-70: Fava bean aquafaba powder with gum dried at 70 °C, FBP-G-60: Fava bean aquafaba powder with gum dried at 60 °C, FBP-G-50: Fava bean aquafaba powder with gum dried at 50 °C.

3.2.4. pH analysis

The pH of muffin samples ranged from 7.42 to 9.10 (Table 2) and muffins produced from fresh FB and fresh FB-G aquafaba had a higher pH compared with WE. However, drying both gum-added and non-gum-added aquafaba decreased the pH of the muffins to the same level as WE muffins. Mustafa et al. (2018) showed that the use of aquafaba from canned chickpea-produced sponge cake with a pH value of 7.43. Yazici et al. (2023) reported that the pH values of gluten-free cakes made from kidney beans, chickpeas, haricot beans, and blacked-eye pea aquafaba ranged from 6.76 to 6.85. Our results showed that the use of dried aquafaba powder can produce a vegan muffin similar to control samples in terms of pH.

3.3. Foam-mat drying

3.3.1. Kinetics of drying

Fig. 2 shows the drying curves of fava bean aquafaba foams. As drying time increased, the *MR* values exponentially decreased. *MR* reduction was faster with an increase in drying temperature. At each temperature, the drying time of gum-added aquafaba was higher than that of the sample without gum. The addition of LBG to the aquafaba significantly retard the drying, due to an increase in the viscosity of samples, causing difficulty for water to evaporate from the aquafaba. Increasing the drying temperature from 50 °C to 70 °C generally decreased the drying times of the sample, with the minimum drying time being observed at the FBP-70 sample. Additionally, FBP-70 samples had a greater drying rate than the other samples (0.823 kg water/kg dry solid. min). These findings showed that the drying temperature and gum addition had a major impact on the transport of moisture. For aquafaba without gum, water diffuses more easily and quickly from the interior to the exterior at all temperature ranges. It is because the porous structures make it simpler for air to flow, accelerating the drying process. Among all aquafaba, FBP-70 samples had the lowest foam density (0.1265 g/ml), meaning a more porous structure that facilitates the movement of moisture from foam (Kilicli et al., 2023). Similar findings were reported for foam-mat drying of lime juice (Dehghannya et al., 2018), tomato puree with green pea aquafaba (Kilicli et al., 2023), and cantaloupe pulp (Salahi et al., 2015).

3.3.2. Mathematical modeling

The experimental *MR* data fit with semi-theoretical (Newton, Middilli &Kucuk) and empirical (Wang & Singh) models (Table 3). According to the highest values of R^2 and lowest values of χ^2 and *RMSE,* the drying kinetics were best described by the Midilli and Kucuk model. The impact of external and internal drying conditions is represented by the *k* and *n* parameters, respectively (Paula et al., 2020). In Newton's model,

Table 4
Effective moisture diffusion coefficient of fava bean aquafaba.

Sample	Diffussion coefficient ($\times10^{-9}$) m^2/s
FBP-70	5.448 ± 0.169[e]
FBP-60	4.192 ± 0.406[d]
FBP-50	2.616 ± 0.168[b]
FBP-G-70	3.347 ± 0.288[c]
FBP-G-60	2.501 ± 0.059[b]
FBP-G-50	1.380 ± 0.026[a]

FBP-70: Fava bean aquafaba powder dried at 70 °C, FBP-60: Fava bean aquafaba powder dried at 60 °C, FBP-50: Fava bean aquafaba powder dried at 50 °C, FBP-G-70: Fava bean aquafaba powder with gum dried at 70 °C, FBP-G-60: Fava bean aquafaba powder with gum dried at 60 °C, FBP-G-50: Fava bean aquafaba powder with gum dried at 50 °C. Mean ± standard deviation is computed from Triplicate samples. Different letters in the same column indicate differences significant at $p < 0.05$.

Table 3
Mathematical modeling of foam-mat drying of aquafaba.

	Samples	a	b	k	n	R^2	RMSE	X^2
Newton	FBP-70	–	–	0.020	–	0.8848	0.124786	0.018167
	FBP-60	–	–	0.011	–	0.8345	0.144222	0.023111
	FBP-50	–	–	0.010	–	0.8710	0.122474	0.016500
	FBP-G-70	–	–	0.011	–	0.9134	0.097895	0.010455
	FBP-G-60	–	–	0.010	–	0.9017	0.102062	0.011364
	FBP-G-50	–	–	0.006	–	0.8280	0.122474	0.016250
Wang &Singh	FBP-70	−0.011	−0.0000074	–	–	0.9831	0.047809	0.003200
	FBP-60	−0.005	−0.000025	–	–	0.9865	0.041231	0.002125
	FBP-50	−0.005	−0.000013	–	–	0.9922	0.030151	0.001111
	FBP-G-70	−0.006	−0.0000014	–	–	0.9962	0.020412	0.000500
	FBP-G-60	−0.005	−0.0000042	–	–	0.9976	0.015811	0.000300
	FBP-G-50	−0.002	−0.000018	–	–	0.9929	0.024807	0.000727
Midilli & Kucuk	FBP-70	1.702	−0.013	0.057	−53.396	0.9883	0.039641	0.003667
	FBP-60	1.123	−0.009	0.108	−11.544	0.9857	0.042426	0.003000
	FBP-50	1.094	−0.007	0.082	−12.160	0.9969	0.019069	0.000571
	FBP-G-70	1.016	−0.006	0.009	−11.569	0.9962	0.020412	0.000625
	FBP-G-60	1.041	−0.006	0.034	−11.790	0.9992	0.009129	0.000125
	FBP-G-50	1.110	−0.005	0.099	−12.476	0.9647	0.055470	0.004444

FBP-70: Fava bean aquafaba powder dried at 70 °C, FBP-60: Fava bean aquafaba powder dried at 60 °C, FBP-50: Fava bean aquafaba powder dried at 50 °C, FBP-G-70: Fava bean aquafaba powder with gum dried at 70 °C, FBP-G-60: Fava bean aquafaba powder with gum dried at 60 °C, FBP-G-50: Fava bean aquafaba powder with gum dried at 50 °C.

as temperature increased, k values increased, proving that the drying kinetics of the fava bean aquafaba samples were significantly impacted by this process variable. However, by raising the air temperature in the Middili & Kucuk model, this parameter failed to exhibit any clear behavior. The suitability of the Middilli & Kucuk model for foam-mat drying of food foams was reported in the literature (Izadi et al., 2020; Nunes et al., 2022; Paula et al., 2020).

3.3.3. Effective moisture diffusion coefficient (D_{eff}) and activation energy (Ea)

D_{eff} values of samples ranged from 1.380 m^2/s to 5.448× 10^{-9} m^2/s (Table 4), in the same range reported for food products (Kian-Pour, 2023). D_{eff} increased with the increase in drying temperature, while it decreased with the addition of gum to samples. FBP-70 showed the highest diffusion coefficient. The drying process depends mainly on this coefficient i.e. larger D_{eff} values can result in faster drying rates. To evaluate and optimize processes involving internal moisture flow, it is crucial to measure D_{eff} as a transfer property. D_{eff} is the sum of all different kinds of water transport from inside of the food to the surface, including capillary flow, water, vapor, hydrodynamic, molecular, and Knudsen diffusions. The interaction between all effective mass transfer parameters is evaluated by the diffusion coefficient. D_{eff} variations during drying are influenced by a variety of factors, including temperature, initial moisture content, porosity, density, and the interaction between different components such as protein, fat, and starch with water. Higher temperatures can elevate D_{eff} because they increase the pressure inside the foam. Higher viscosity, as opposed to temperature, can result in resistance to the diffusion and passage of moisture through capillary tubes (Dehghannya et al., 2018). In our study, when LBG was added to aquafaba, the D_{eff} decreased, attributable to the increase in the viscosity of aquafaba after the addition of gum. Since more air bubbles can enhance moisture removal from samples, foam-like samples have a greater D_{eff} than non-foam samples (Kian-Pour et al., 2024). Our results were consistent with the other study. It was stated that as whey foams dried at 40–80 °C, the D_{eff} ranged from 1.375 to m^2/s 4.881 × 10^{-9} m^2/s (Paula et al., 2020). However, our D_{eff} values were lower than those reported by (Kilicli et al., 2023). Authors used green pea aquafaba to produce tomato powder and D_{eff} ranged from 0.99 m^2/s to 4.15 × 10^{-7} m^2/s. It can be related to the lower thickness of foam (5 mm) in their study compared with our study (10 mm) (Dehghannya et al., 2018; Kilicli et al., 2023). The E_a is determined from the curve of Ln D_{eff} against 1/T. The E_a of fava bean aquafaba powder without gum and fava bean aquafaba powder with gum were calculated as 33.87 kJ/mol and 40.93 kJ/mol, respectively, within the normal range of 13 kJ/mol to 110 kJ/mol for food products (Paula et al., 2020). The addition of gum to aquafaba increased the E_a of samples. E_a values evaluated in our study agree with those reported by other studies about foam-mat drying of white cheese foam (21.35 to 58.81 kJ/ mol) (Izadi et al., 2020), whey foam (29.61 kJ/ mol) (Paula et al., 2020), cantaloupe (31.714–33.04 kJ/ mol) (Salahi et al., 2015), and carrot foam (40.5–66.2 kJ/ mol) (Nunes et al., 2022).

Table 5
Bulk, tapped and particle densities of foam mat dried fava bean aquafaba powders.

Sample	Bulk density (g/ml)	Tapped density (g/ml)	Particle density (g/ml)
FBP-70	0.294 ± 0.006^{b}	0.362 ± 0.018^{ab}	2.048 ± 0.155^{a}
FBP-60	0.387 ± 0.019^{c}	0.453 ± 0.017^{c}	3.555 ± 0.385^{bc}
FBP-50	0.397 ± 0.053^{c}	0.423 ± 0.061^{bc}	4.505 ± 0.438^{d}
FBP-G-70	0.222 ± 0.009^{a}	0.285 ± 0.003^{a}	1.784 ± 0.149^{a}
FBP-G-60	0.272 ± 0.019^{ab}	0.329 ± 0.012^{a}	3.038 ± 0.185^{b}
FBP-G-50	0.305 ± 0.016^{b}	0.350 ± 0.027^{ab}	4.237 ± 0.279^{cd}

FBP-70: Fava bean aquafaba powder dried at 70 °C, FBP-60: Fava bean aquafaba powder dried at 60 °C, FBP-50: Fava bean aquafaba powder dried at 50 °C, FBP-G-70: Fava bean aquafaba powder with gum dried at 70 °C, FBP-G-60: Fava bean aquafaba powder with gum dried at 60 °C, FBP-G-50: Fava bean aquafaba powder with gum dried at 50 °C. Mean ± standard deviation is computed from Triplicate samples. Different letters in the same column indicate differences significant at $p < 0.05$.

3.4. Characterization of Aquafaba powder

3.4.1. Bulk, tapped and particle densities

Bulk density is defined as the ratio of the powder's weight to its occupied volume (without being tapped). The ratio of powder weight to occupied volume following up-and-down movement and tapping is also known as tapped density. The bulk density of aquafaba powders ranged from 0.222 g/ml to 0.397 g/ml (Table 5). As the drying temperature increased, the bulk density significantly decreased, associated with the faster removal of moisture from aquafaba at higher temperatures. Generally, tapped density values showed the same trends seen for bulk density (Table 5). Aquafaba samples dried at 50 °C showed the highest bulk and tapped density in both cases of gum-added and non-gum-added samples. The ratio of weight to occupied volume of powder particles is known as particle density. The particle density of aquafaba ranged from 1.784 g/ ml to 4.505 g/ ml (Table 5). As the drying temperature increased, particle density decreased for all samples, in agreement with other studies (Aslan & Ertaş, 2021; Dehghannya et al., 2019). Similar results were reported about decreasing the bulk density of powders dried at higher temperatures. Aslan and Ertaş (2021) reported that as temperature of foam-mat drying increased from 50 °C to 70 °C bulk density of chickpea aquafaba decreased from 0.762 g/ml to 0.708 g/ml and tapped density reduced from 0.815 g/ml to 0.740 g/ml. Higher drying temperatures are linked to a decrease in the density of powdered materials due to moisture elimination (Dehghannya et al., 2019). For industrial packaging, bulk, and tapped densities are essential characteristics since they indicate the volume occupied by the powder. Some aspects of powder quality, including rehydration, packing, marketing, transportation, and product physical attributes, have been directly linked to bulk density (Aslan & Ertaş, 2021). It is possible to store powders with a larger bulk density in smaller packages. Changes in air incorporation during the foaming process cause significant differences in bulk density. Particle sizes and moisture concentration also affect powder density. Powder with higher moisture causes particles to have a stronger tendency to stick together, creating more holes between

Table 6
Porosity, flowability, cohesiveness and wettability of foam mat dried fava bean aquafaba powders.

Sample	Porosity (%)	Flowability	Cohesiveness	Wettability (min)
FBP-70	82.28 ± 0.99^{a}	18.69 ± 2.26^{bc}	1.23 ± 0.03^{bc}	0.97 ± 0.05^{a}
FBP-60	87.13 ± 1.69^{bc}	14.66 ± 1.14^{abc}	1.17 ± 0.01^{abc}	2.11 ± 0.05^{b}
FBP-50	90.48 ± 2.17^{cd}	6.95 ± 1.04^{a}	1.08 ± 0.01^{a}	3.44 ± 0.32^{cd}
FBP-G-70	83.96 ± 1.30^{ab}	21.30 ± 3.04^{c}	1.27 ± 0.04^{c}	2.88 ± 0.23^{c}
FBP-G-60	89.15 ± 0.28^{cd}	17.33 ± 4.06^{bc}	1.21 ± 0.06^{bc}	3.91 ± 0.27^{d}
FBP-G-50	91.74 ± 0.16^{d}	12.70 ± 4.10^{ab}	1.14 ± 0.05^{ab}	11.34 ± 0.38^{e}

FBP-70: Fava bean aquafaba powder dried at 70 °C, FBP-60: Fava bean aquafaba powder dried at 60 °C, FBP-50: Fava bean aquafaba powder dried at 50 °C, FBP-G-70: Fava bean aquafaba powder with gum dried at 70 °C, FBP-G-60: Fava bean aquafaba powder with gum dried at 60 °C, FBP-G-50: Fava bean aquafaba powder with gum dried at 50 °C. Mean ± standard deviation is computed from Triplicate samples. Different letters in the same column indicate differences significant at $p < 0.05$.

them and increasing the amount of powder bulk volume (Dehghannya et al., 2018).

3.4.2. Porosity, Flowability, cohesiveness and wettability

The porosity of the aquafaba powders ranged from 82.28 % to 91.74 % (Table 6). As the drying temperature increased, porosity significantly decreased. As the temperature rose, the structure of the foam and bulbs collapsed, decreasing the porosity of the powder. Also, less air space between the particles may be the cause of the reduction in the porosity at higher temperatures. The results of this study are in line with other studies (Aslan & Ertaş, 2021; Dehghannya et al., 2019). Two crucial characteristics that show the flow quality of dry powder particles are flowability and cohesiveness. The values for flowability and cohesiveness of aquafaba powder are shown in Table 6. Significant differences in the Carr index and Hausner ratio of the sample dried at 50 °C were observed compared with other drying temperatures. Increases in the Carr index of samples at higher temperatures confirm that high drying temperature negatively affected the flowability of powder, likely due to the greater protein denaturation. Consequently, this will decrease the flowability of the powder. Better flow quality of dry powders is associated with lower cohesiveness and flowability values. Therefore, the optimal flowability of fava bean aquafaba powder can be attained when the drying temperature is set at 50 °C. The ability of a liquid to permeate powder bulk by capillary forces is known as wettability. The wettability of samples ranged from 0.97 min to 11.34 min (Table 6). Increases in drying temperature caused a reduction in the wettability time of aquafaba powders. A drying temperature of 70 °C can produce a dried powder with better wettability. Fast and complete wettability is a desirable quality in a powder (Dehghannya et al., 2018**).** Our results are in agreement with other studies (Aslan & Ertaş, 2021). The sample with the best wettability value was found to be FBP-70 powder which can be wet less than one minute. Therefore, the FBP-70 sample can be a good candidate for usage in different food products at an industrial scale.

4. Conclusions

Fava bean aquafaba was utilized to create an eggless vegan muffin with good techno-functional properties. Locust- bean-gum (LBG) was added to the aquafaba to enhance its foaming properties and improve the overall quality of the vegan muffins. Fresh aquafaba was subjected to foam-mat drying to produce a dried powder and extend the shelf life of the aquafaba. The addition of LBG to aquafaba increased the foam stability and decreased the foam drainage value. Besides, it decreased the baking loss of muffins and increased its volume. The Middili & Kucuk drying model showed the best fit with experimental data. The fava bean aquafaba dried at 70 °C showed very good foam capacity, foam stability, the minimum foam drainage volume, the highest muffin volume, and the lowest wettability time compared with other temperatures. Further research is needed to develop new food products using fava bean aquafaba for those looking to reduce their egg consumption. Additionally, studying the use of different hydrocolloids to enhance the foaming properties and examining their impact on the drying behavior of foam could be valuable areas for future research. This study has confirmed that foam-mat drying of fava bean aquafaba at 70 °C will produce instant FB aquafaba powder with easy use at home and industrial scale.

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CRediT authorship contribution statement

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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

Data will be made available on request.

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