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Potentials of soybean aquafaba as viable whole egg substitute in cupcakes

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Abstract

The present work investigated the potential of soybean aquafaba as a viable egg substitute in cupcakes. Soybean seeds were soaked for 16 h, and then cooked at a 1:4 bean-to-water ratio for 4 h at 98°C. The resulting aquafaba was used to produce cupcake samples with varying aquafaba-to-egg substitution levels (0, 25, 50, 75, and 100%), and the quality properties of the cakes were evaluated. Significant differences ($p < 0.05$) were observed in the proximate composition of the cake samples. Moisture content ranged from 10.03% to 12.33%, while protein content varied from 4.03% to 6.33%. Higher egg substitution levels increased baking loss and crust colour properties, but decreased specific volume. Significant differences ($p < 0.05$) were also noted in cake texture, with hardness, resilience, springiness, cohesiveness, chewiness, and gumminess decreasing as egg substitution increased. Sensory evaluation revealed a decrease in overall acceptability with increased egg substitution. However, fluffiness and aftertaste improved significantly ($p < 0.05$) at higher substitution levels. The sample with a 25% egg substitution rate was the most accepted, having a higher overall acceptability value (7.85) than the control sample (7.75). Aquafaba substitution significantly increased ($p < 0.05$) moisture content and water activity over storage time. The total viable microbial count increased during storage for all samples, but the 100% egg-substituted cake exhibited the lowest microbial growth. In conclusion, soybean aquafaba could serve as an effective egg substitute in cupcakes at all tested levels, with the 75% substitution level being the most acceptable.

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Introduction

Eggs are important in the human diet because of their high nutritional value, especially in terms of protein content, as they are among the richest protein sources (Yazici and Ozer, 2021). In addition, eggs have several functional properties, including foaming, tenderising, emulsifying, improving nutritive value and texture, colouring, flavouring and binding (Ashwini *et al*., 2009; Ratnayake *et al.,* 2012; Wilderjans *et al.,* 2013).

Despite the excellent properties of eggs, there has been a growing consumer demand for egg replacers that can mimic some, if not all, of the functional roles of eggs in foods. This demand stems mainly from health problems associated with egg consumption, which include salmonellosis, phenylketonuria (an amino acid metabolism disorder and egg allergy), influenza, and cardiovascular diseases linked to cholesterol (Pires *et al*., 2014; Pimentel *et al.,* 2014; Lin *et al*., 2017b; Zhu *et al.,* 2018).

Other reasons for egg replacement demand include dietary preferences such as those of vegetarians and vegans (Janssen *et al.,* 2016; Sharif *et al*., 2018), religious beliefs, environmental concerns, and economic factors such as high egg costs and difficulties in egg transportation (Lin *et al*., 2017a).

Various studies have been carried out to develop alternative egg replacers (ERs), which can be used partially or completely, instead of eggs in cake formulations, such as soybean protein isolates (Lin *et al*., 2017a), soy milk (Rahmati and Mazaheri, 2015; Hedayati and Mazaheri, 2018), lentil protein (Jarpa-Parra *et al.,* 2017), pea protein (Lin *et al*., 2017a), whey protein (Paraskevopoulou *et al*., 2015), hydrocolloids and emulsifiers (Rahmati and Tehrani, 2014; Shao *et al*., 2015), and even bovine plasma (Johnson *et al*.,1979; Lee *et al.,* 1991). Unfortunately, many of these ERs had significantly lower performance than eggs did, especially in terms of foam stability. Egg proteins play important roles in cake volume and texture because they have unique foaming, emulsifying, and heat coagulation

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properties (Ashwini *et al.,* 2009; Abu-Ghoush *et al*., 2010). These properties are indeed difficult to replicate when proteins from other sources are used, even when they are used in combination.

To overcome some of the limitations of other ERs, research interest has recently focused on the potential of aquafaba as a more effective ER. Aquafaba is a viscous liquid obtained from the cooking water of legumes, particularly chickpeas (BAKERpedia, 2020). Aquafaba has good foaming, emulsifying, and thickening features similar to those of eggs (Mustafa *et al*., 2018). These unique properties have been attributed to its protein, carbohydrate, and saponin contents (Stantiall *et al*., 2018), and appropriate pH and NaCl concentration (Buhl *et al*., 2019).

Aquafaba has been used as an egg white substitute in food foams and emulsions (Buhl *et al.,* 2019), egg yolk substitute in mayonnaise (Raikos *et al*., 2019; Muhialdin *et al*., 2021), cakes (Aslan and Ertaş, 2020), and lima bean aquafaba in eggless cupcakes (Mustafa *et al*., 2018; Nguyen *et al.,* 2020; Silva *et al*., 2022).

Most studies on aquafaba utilisation in food formulations are focused on aquafaba, limited to aquafaba produced from chickpea, lentil, and lupin (Bird *et al*., 2017; Shim *et al*., 2018; He *et al*., 2019; Raikos *et al.,* 2019; Buhl *et al*., 2019). Unfortunately, chickpea and lupin are not commonly available in Nigeria and other African countries, highlighting the need to explore a more readily available and affordable source of aquafaba. Soybeans are commercially cultivated, and readily available in Nigeria, making it a potential source of affordable aquafaba, to either wholly or partially replace egg, and perform similar functional roles in eggs. Given the rising cost of eggs and associated challenges, the present work aimed to evaluate the potential of soybean aquafaba as ER in cake production.

Materials and methods

Raw materials (sample collection)

Soybean seeds were procured from the International Institute of Tropical Agriculture (IITA), Nigeria, whereas wheat flour, sugar, shortening, whole egg, salt, baking powder, and vanillin were obtained from the Ibadan local market (Ojo market). Soybean seeds were manually cleaned to remove dust and foreign materials, and then washed. All seed was stored at room temperature (20 - 22°C) until further analysis.

Aquafaba preparation

Soybean seeds (1000 g) were soaked in excess water for 16 h, with the water changed every 4 h. After soaking, the seeds were drained and cooked at a 1:4 bean-to-water ratio for 4 h at 98°C to produce soybean aquafaba. The aquafaba was then separated from the cooked grains, cooled, and stored at 4°C until analysis.

Batter preparation and baking procedure

The cake batter was prepared using wheat flour (275 g), shortening (250 g), sugar (200 g), eggs (180 g), and baking powder (9 g). A control cake sample was made using 180 g of eggs without the incorporation of aquafaba (AQ). Various cake samples were prepared by replacing eggs with AQ at different substitution levels: 25, 50, 75, and 100%.

The process began with creaming sugar and eggs in a Binatone mixer (Model KM-1000) at high speed for 20 min. Subsequently, the remaining ingredients were added and mixed for an additional 5 min. For each cake, 60 g of batter was poured into a cupcake pan, and baked at 150°C for 30 min in a preheated oven (Memmert Model 30-1060, Memmert-GmbH, D-91126, Schwabach, Germany). After baking, the cakes were left to cool at room temperature for 60 min before analysis.

Determination of nutritional properties of cake samples

Determination of moisture content

The moisture content was determined following the hot air oven method described by AOAC (2010). Two (2) g samples were transferred into the moisture dish, and dried for 23 h at 100 - 105°C. After drying, the sample was cooled by being placed in desiccators before being weighed again to obtain the final weight. The percentage content of each sample was then calculated using Eq. 1:

$$Moisture\ content\ (\%) = \frac{W1 - V1 \times 100}{W1 - W2} \qquad \text{(Eq. 1)}$$

where, W1 = weight of sample in mL; W2 = weight of crucible + sample before drying; and V1 = weight of crucible + sample after drying.

Determination of ash content

The ash content was determined following the AOAC (2010) method. An ash crucible (porcelain) containing the weighed cake sample (2 g) was placed inside a muffle furnace operated at 550°C for 6 h with a stepwise increase in temperature to burn off moisture and all organic constituents. The ash content was recorded as the weight of the residue after incineration. The percentage ash content of each sample was then calculated using Eq. 2:

$$Ash\ content\ (\%) = \frac{W2 - W1 \times 100}{V1} \quad \text{(Eq. 2)}$$

where W1 = weight of empty crucible; V1 = volume of sample; and W2 = weight of ash + crucible.

Determination of protein content

The crude protein content (percentage of nitrogen × 6025) was determined by the micro Kjeldahl method (AOAC, 2010).

Determination of crude fibre

The crude fibre determined according to Moller (2014) using the FOSS FibertecTM 2010 model. Briefly, 1 g of defatted cake samples was sequentially treated with hot H_2SO_4 (containing 1.25%) and hot NaOH (containing 1.25%) under reflux for 30 min. Filtration was performed, and the residue was dried in an oven, and incinerated in a muffle furnace sequentially.

The loss in weight was measured, and the percentage of crude fibre was calculated using Eq. 3:

$$Crude\ fibre\ (\%) = \frac{Loss\ in\ weight\ (g)\ after\ ignition \times 100}{Weight\ of\ the\ original\ sample\ (g)} \quad \text{(Eq. 3)}$$

Determination of crude fat content.

The crude fat content was determined following the AOAC (2010) method. Briefly, 3 g of the cake samples was extracted with hexane using the FOSS SoxtecTM 8000 model, and the solvent was evaporated to obtain the fat. The difference between the initial and final weights of the extraction cup was recorded as the crude fat content.

Determination of carbohydrate content

The carbohydrate content was determined by difference as described by AOAC (2010) using Eq. 4:

Carbohydrate content (%) = 100 – (% protein + % fat + % ash + % crude fibre + % moisture) (Eq. 4)

Determination of physical properties of cake samples

Baking loss

The baking loss (%) was calculated by dividing the weight difference of the batter, before and after baking, and cooling, using Eq. 5:

$$\text{Weight loss (\%)} = \frac{Wbatter - Wcake \times 100}{Wbatter} \quad \text{(Eq. 5)}$$

where, Wbatter and Wcake = weights of the batter and cake before and after baking, respectively.

Colour parameters

Since the L*, a*, and b* colour system produces a uniform colour distribution, and is closest to human perception, it was utilised to determine the colour of the cake samples. A xenon lamp was used as the light source, and a chromameter (CR410, Konica Minolta, Japan) was used to quantify the colour of the cake samples in terms of laboratory values. The chromameter probe was placed onto the top surface of the cake samples within a clear nylon sample, which allowed for uniform scanning under adequate lighting.

Cake specific volume

The cake specific volume (cm^3/g) was calculated by dividing the cake volume by its mass. The cake volume (cm^3) was measured in triplicate by millet seed displacement, and the mass (g) was measured using an analytical balance as described previously (Bedoya-Pareles and Steel, 2014).

Textural properties

The textural characteristics were measured by chopping the cake into 2 × 2 × 2 cm cubes, following the method outlined by Nguyen *et al*. (2020). The texture analyser was adjusted to 5 mm/s, and it underwent two compression cycles and 50% deformation in comparison to its initial configuration. A TA4/1000 cylinder, which has a diameter of 38.1 mm and a thickness of 20 mm was utilised, and the compression force was 5 g.

Sensory analysis

The sensory evaluation of the cake samples involved 20 semi trained panellists selected from staff of the International Institute of Tropical Agriculture in Nigeria who were chosen on the basis of their interest, were non-smokers, and had no food allergies. The analysis took place in a room illuminated with daylight, and the samples were presented randomly.

The sensory attributes, including crumb colour, crust colour, fluffiness, taste, aftertaste, flavour, aroma, texture, appearance, and overall acceptability, were rated using a 9-point hedonic scale. This scale ranged from 1 (extremely disliked) to 9 (extremely liked) (Ihekoronye and Ngodddy, 1985).

Storage studies

The cake samples were stored in sterile sample bags at ambient temperature for eight days, simulating typical storage conditions in developing countries, where cakes are commonly kept at room temperature in homes, bakeries, and retail outlets. The moisture content, water activity (a_w), total viable count, and yeast and mould count were determined on days zero, four, and eight.

Microbial analysis

Total Viable Count

The pour plate method according to Harrigan and McCane (1976) was performed. Briefly, 9 mL of Ringer's solution were homogenised with 1 g of cake sample. This mixture was further diluted to obtain a concentration of 10^{-2}. From each dilution factor, 0.1 mL of inoculum was aliquoted onto empty Petri dish, and 15 mL of molten sterile nutrient agar medium was added. The plates were then swirled gently to mix the inoculum with the medium. Following a 24-h incubation period at 37°C, bacterial colonies that developed on the plates were enumerated using a colony counter and expressed as colony forming units per gram (CFU/g) using Eq. 6:

$$Microbial\ count\ \left(\frac{CFU}{g}\right) = \frac{Number\ of\ colonies \times dilution\ factor}{Volume\ of\ aliquot} \quad \text{(Eq. 6)}$$

where, CFU = colony-forming unit.

Yeast and Mould Count

Yeast and mould count was performed according to Prescott *et al*. (2005), similar to Total Viable Count, except the fungal agar was Sabouraud Dextrose agar (SDA), and the incubation period was 48 h. Eq. 6 was also used to obtain the CFU/g.

Experimental design and statistical analysis

The experiment employed a complete randomised design (CRD). The mean values and standard deviations were computed using one-way analysis of variance (ANOVA) using the Statistical Package for the Social Sciences (SPSS) version 20. Duncan's New Multiple Range Test was applied to separate the means. Statistical significance was accepted at $p < 0.05$ (Steel and Torrie, 1980).

Results and discussion

Properties of cake samples made with soybean aquafaba

Figure 1 shows the images of cake samples produced with different levels of soybean aquafaba as an egg substitute. Noticeable differences in appearance were observed, with higher egg substitution levels resulting in reduced volume, altered texture, and structural changes in the cakes.

Proximate properties of cake samples made with soybean aquafaba

The proximate compositions of cakes made with different levels of soybean aquafaba as an egg substitute are presented in Table 1. Significant differences ($p < 0.05$) were observed among all cake samples in terms of proximate parameters. Moisture content ranged from 10.03 to 12.33%, with the control cake having the lowest moisture content, and the C5 cake (100% aquafaba substitution) having the highest. The increase in moisture content with higher aquafaba levels may be attributed to the naturally high moisture content of aquafaba. This observation agreed with Mustafa *et al.* (2018), who reported similar moisture content in sponge cakes incorporating aquafaba. Additionally, He *et al.* (2021) reported that the moisture content of aquafaba-based cakes ranged from 93.5 to 95.1%, while El-Shimy (2013) observed a moisture content of 6.21% in conventional cakes.

The proximate composition of chickpea aquafaba, as determined by Graziele *et al*. (2022), consisted of 94.4% moisture, 3.4% carbohydrates, 1.2% protein, 0.5% ash, 0.5% fibre, and 0.1% fat. In contrast, the moisture content of whole eggs has been reported as 76.25 g/100 g (Rachtanapun *et al.,* 2022).

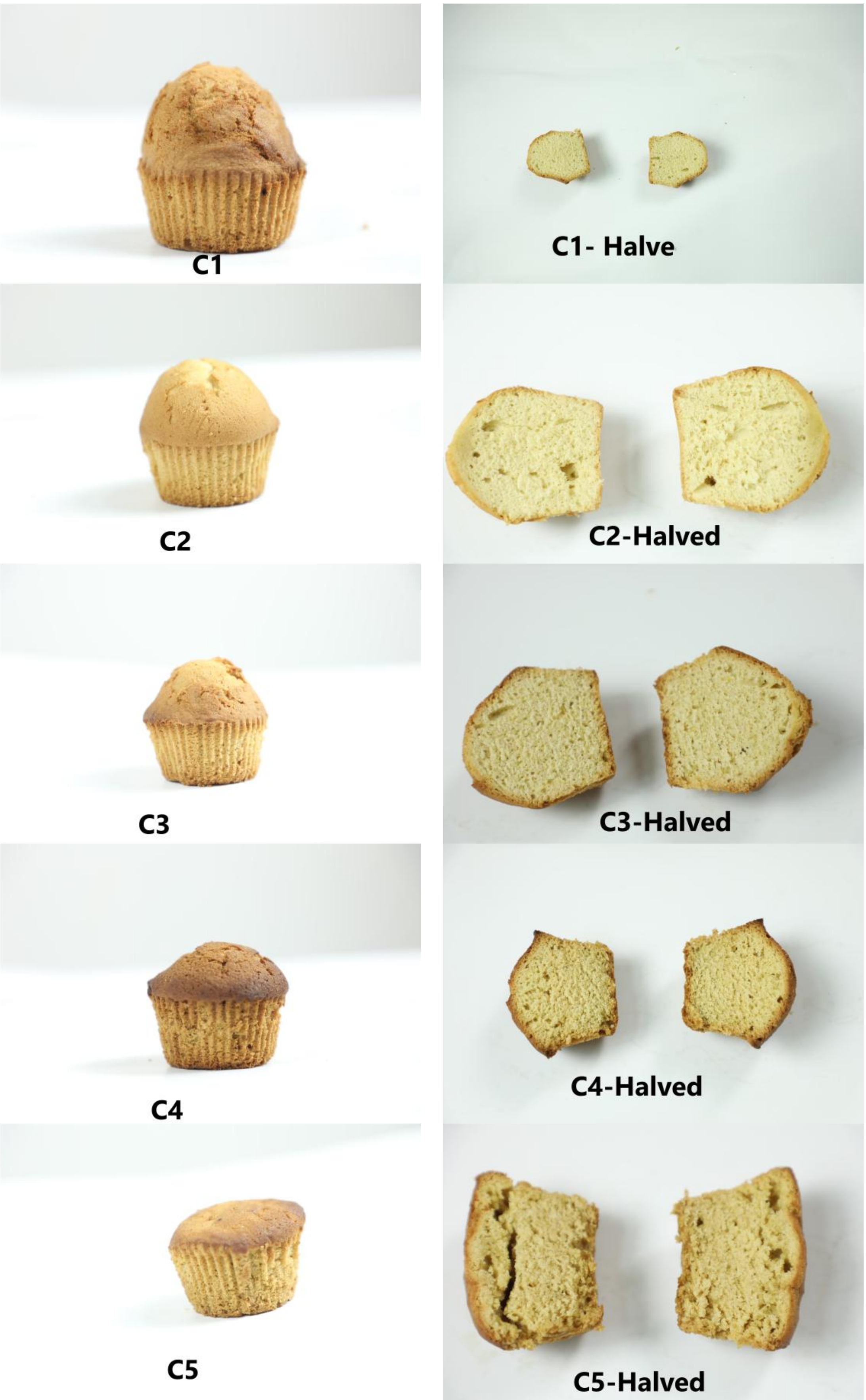

Figure 1. Pictorial representation of cake samples prepared with varying levels soybean aquafaba. C1: 0% aquafaba + 100% egg; C2: 25% aquafaba + 75% egg; C3: 50% aquafaba + 50% egg; C4: 75% aquafaba + 25% egg; and C5: 100% aquafaba + 0% egg.

Table 1. Proximate properties of cake samples.

Property/ Sample	Moisture	Ash	Protein	Fat	Fibre	Carbohydrate
C1	10.14 ± 0.38^e	1.63 ± 0.01^a	6.33 ± 0.25^a	18.64 ± 9.08^a	6.59 ± 0.19^c	55.81 ± 0.07^c
C2	10.03 ± 0.33^d	1.36 ± 0.06^b	5.97 ± 0.00^a	18.40 ± 0.29^a	6.53 ± 0.03^c	50.23 ± 0.19^e
C3	11.99 ± 0.21^c	1.25 ± 0.05^{bc}	5.36 ± 0.13^b	18.35 ± 0.03^a	6.24 ± 0.07^c	54.89 ± 0.59^d
C4	12.09 ± 0.11^b	1.17 ± 0.06^{cd}	4.56 ± 0.25^c	18.23 ± 0.21^a	5.39 ± 0.42^a	57.04 ± 0.38^b
C5	12.33 ± 0.04^a	1.09 ± 0.05^d	4.03 ± 0.00^d	17.86 ± 0.27^a	5.21 ± 0.15^b	58.31 ± 0.32^a

Means followed by different lowercase superscripts within similar column are significantly different ($p < 0.05$) according to Duncan's test. C1: 0% aquafaba + 100% egg; C2: 25% aquafaba + 75% egg; C3: 50% aquafaba + 50% egg; C4: 75% aquafaba + 25% egg; and C5: 100% aquafaba + 0% egg.

The higher moisture content in aquafaba-substituted cakes may negatively impact shelf life, as moisture plays a critical role in microbial activity and spoilage. Cakes with 75 and 100% aquafaba substitution, in particular, may be more susceptible to textural changes and microbial growth during storage. While higher moisture content generally results in a softer, more tender cake with improved mouthfeel, excessive moisture can lead to undesirable textural changes such as gumminess, stickiness, or a dense structure.

Protein content ranged from 4.03 to 6.33%, decreasing as aquafaba substitution increased. Bird *et al*. (2017) and Aslan and Ertaş (2020) reported protein contents of 0.08 g/100 g for aquafaba, and 9.98% for whole eggs, respectively. The protein content of the control cake in the present work was lower than the 9.98% reported by Aslan and Ertaş (2020), but comparable to the 6.28% reported by El-Shimy (2013). Aslan and Ertaş (2020) also found that increasing egg replacement with aquafaba in traditional cake formulations led to a gradual decrease in protein content (from 9.98 ± 0.21 to 6.39 ± 0.21 mg/100 g).

Ash content ranged from 1.09 to 1.63%, decreasing with higher aquafaba substitution. This decrease may be attributed to the lower ash content of aquafaba compared to eggs. A similar trend was observed for crude fibre content. Aslan and Ertaş (2020) also reported a decrease in ash content with increasing aquafaba substitution.

Physical properties of cake samples made with soybean aquafaba

Significant differences ($p < 0.05$) were observed among the samples in terms of baking loss (BL) (Figure 2), with values ranging from 7.88 to 11.69%. The control sample had the highest BL value. A general increase in BL was observed as the level of aquafaba substitution increased. This higher BL in aquafaba-containing samples can be attributed to its lower water-binding capacity compared to eggs, leading to greater moisture evaporation during baking (Ratnayake *et al.,* 2012). This agreed with Mustafa *et al.* (2018) and Aslan and Ertaş (2020), who also reported an increase in BL with higher egg substitution using chickpea aquafaba, although the differences were not statistically significant.

Baking loss is defined as the process in which gas is produced, and vapour pressure increases due to the expansion of liquids when heat permeates the batter during baking (Kim *et al.,* 2012). If excessive gas escapes, the textural qualities of the cake may be negatively affected. This suggests that a high level of aquafaba substitution could reduce cake texture quality.

The cake samples also showed significant differences in specific volume, with values ranging from 2.13 to 3.38 mL/g. The lowest specific volume was observed in the C1 sample, while the C5 sample (100% aquafaba substitution) had the lowest specific volume among the aquafaba-containing cakes. A decrease in specific volume was observed with increasing aquafaba substitution. High-volume cakes are generally preferred by consumers, as they are associated with increased lightness and fluffiness. According to Graziele *et al*. (2022), cakes with a higher proportion of eggs tend to have greater volume because albumin proteins help sustain the foam structure, enhancing air retention, and improving leavening. Consequently, the final cake structure becomes more aerated and well-defined (Lu *et al.,* 2010). Similar results were reported by Tan *et al.* (2015), who found that egg-free cake samples exhibited lower volume (Aslan and Ertaş, 2020). The decrease in specific volume with increasing aquafaba substitution would consequently lead to denser and less fluffy cakes. This is contrary to consumer's preference for a light and fluffy textured product. This

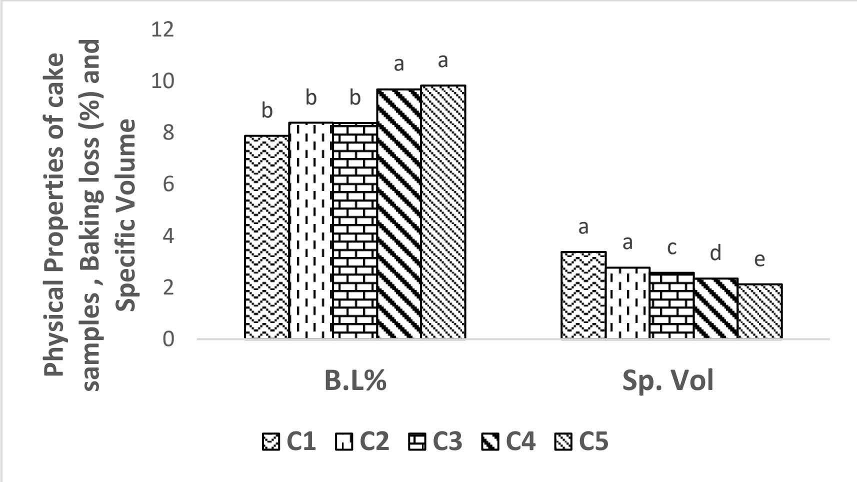

Figure 2. Physical properties of cake samples produced with varying levels of soybean aquafaba. Means with different lowercase letters within similar parameter are significantly different ($p < 0.05$) according to Duncan's test. C1: 0% aquafaba + 100% egg; C2: 25% aquafaba + 75% egg; C3: 50% aquafaba + 50% egg; C4: 75% aquafaba + 25% egg; and C5: 100% aquafaba + 0% egg.

is due to aquafaba's weaker foaming capacity, lower gas retention, higher moisture content, and reduced structural stability compared to eggs.

Colour properties of cake samples made with soybean aquafaba

Significant differences were observed among the samples in all measured colour parameters for both the crumb and crust (Table 2). The crust lightness (L*) ranged from 48.19 to 60.90. Cakes with lower egg substitution exhibited higher lightness, while the 100% egg-substituted sample had the lowest brightness. This decrease in lightness may be attributed to the darker colour of aquafaba. Similar findings were reported by a previous study, who found that cakes made with kidney bean aquafaba had lower brightness (59.89) compared to those made with egg whites. Aslan and Ertaş (2020) also observed a decrease in lightness with aquafaba addition. The presence of simple sugars and polysaccharides in aquafaba contributes to Maillard and caramelisation reactions, leading to darker coloration (Shim *et al.,* 2018). Nguyen *et al.* (2020) similarly reported a decrease in lightness with higher aquafaba substitution, whereas Silva *et al*. (2022) observed increased lightness when aquafaba was combined with lentil protein and citric acid. They also noted greater moisture loss in aquafaba-based egg substitutes.

The a* (redness) values ranged from 4.82 to 13.34, increasing with higher egg content. This agreed with Aslan and Ertaş (2020) for cakes containing chickpea aquafaba. The b* (yellowness) values varied from 15.73 to 38.40, with a general decrease as egg substitution increased. The higher b* value in the control cake was likely due to the greater amount of egg yolk, which imparted a stronger yellow hue compared to aquafaba-containing cakes. This decrease in yellowness with increased egg substitution also agreed with Aslan and Ertaş (2020).

Table 2. Colour properties of cake samples.

Sample	Crust colour			Crumb colour		
	L*	a*	b*	L*	a*	b*
C1	59.26 ± 0.98^a	10.23 ± 0.24^b	21.51 ± 0.62^{bc}	69.68 ± 0.63^b	3.39 ± 0.78^b	27.57 ± 0.74^c
C2	60.90 ± 0.74^a	10.34 ± 0.28^a	19.40 ± 0.18^a	73.52 ± 0.00^c	3.24 ± 0.12^b	26.97 ± 0.08^d
C3	54.93 ± 1.12^b	10.08 ± 0.49^b	18.17 ± 0.54^{cd}	70.64 ± 0.74^b	3.56 ± 0.04^a	25.97 ± 0.63^b
C4	55.69 ± 1.81^b	9.07 ± 0.04^c	15.73 ± 2.95^d	64.22 ± 0.40^a	4.28 ± 0.09^c	24.74 ± 0.85^a
C5	48.19 ± 1.15^c	8.82 ± 0.55^d	14.24 ± 1.07^b	63.22 ± 0.76^a	5.68 ± 0.13^d	23.57 ± 0.42^e

Means followed by different lowercase superscripts within similar column are significantly different ($p < 0.05$) according to Duncan's test. C1: 0% aquafaba + 100% egg; C2: 25% aquafaba + 75% egg; C3: 50% aquafaba + 50% egg; C4: 75% aquafaba + 25% egg; and C5: 100% aquafaba + 0% egg.

For the crumb, lightness (L*) ranged from 63.22 to 69.68, with C2 sample having the highest value, and C5 sample the lowest. As aquafaba substitution increased, L* values decreased, likely due to its darker colour. The a* (redness) values ranged from 2.56 to 5.68, generally increasing with higher aquafaba levels. The reddish-brown hue of aquafaba may have contributed to the enhanced redness of the cakes. Conversely, yellowness (b*) decreased as aquafaba substitution increased, likely due to the decrease in egg yolk, which contributes to a yellow hue. Similar findings were reported by Mustafa *et al*. (2018), as well as Gómez *et al.* (2010) and Levent and Bilgiçli (2013), who observed lower L* values and higher b* values in aquafaba-containing cakes.

Textural properties of cakes made with soybean aquafaba

Significant differences ($p < 0.05$) were observed among the samples in all evaluated textural parameters, as shown in Table 3. Hardness values ranged from 5.05 N (C5) to 20.03 N (C1), with hardness decreasing as aquafaba substitution increased. Mustafa *et al*. (2018) reported similar findings, noting lower hardness in aquafaba cakes compared to egg-white-based cakes. The distinct foaming, emulsifying, and heat-coagulating properties of egg white proteins contribute significantly to cake volume, resulting in a well-aerated structure with greater firmness. In contrast, aquafaba has lower foam capacity and stability than eggs, leading to softer cakes with reduced aeration and structure (Ashwini *et al.,* 2009).

Resilience values ranged from 9.33% (C5) to 29.06% (C1), decreasing with higher levels of egg substitution. A more resilient cake maintains a soft and tender crumb while being sturdy enough to withstand slicing and serving without collapsing.

Springiness values ranged from 31.39 mm (C5) to 89.82 mm (C1). Springiness refers to the ability of a cake to recover its shape after deformation. The lower foaming ability of aquafaba negatively impacted crumb structure, leading to reduced springiness in aquafaba cakes (Helal and Nassef, 2021).

Cohesiveness values ranged from 0.41 (C4) to 0.83 (C1), with a general decrease as egg substitution increased. Cohesiveness measures the internal bonding strength of the cake and its ability to maintain structural integrity before breaking. Lower cohesiveness results in a crumblier texture, making slicing more challenging.

Chewiness values ranged from 1.188 Nmm (C5) to 15.44 Nmm (C1). Chewiness is the force required to prepare food for swallowing, and is a function of hardness, cohesiveness, and elasticity. Similarly, gumminess values ranged from 2.08 N (C5) to 16.67 N (C1), decreasing with higher aquafaba substitution. Helal and Nassef (2021) reported a similar trend in cakes made with chickpea aquafaba. Gumminess refers to the degree of chewiness or stickiness in a food product, which can influence mouthfeel. While higher gumminess may result in a denser and stickier texture, this characteristic can be desirable for individuals who prefer a more compact cake.

Sensory scores of cakes samples made with soybean aquafaba

The effects of replacing eggs with soybean aquafaba on the sensory attributes of the cakes are presented in Table 4. Significant differences ($p < 0.05$) were observed among the samples for all sensory parameters except taste and flavour.

The sensory scores for crumb and crust colour ranged from 6.45 to 8.00 and 6.50 to 7.50, respectively. The C1 sample received the highest scores for both parameters, while C5 sample had the lowest. Cakes with higher aquafaba substitution appeared darker, likely due to the brownish hue of aquafaba. This agreed with Aslan and Ertaş (2020), who reported lower colour scores in cakes where eggs were replaced with chickpea aquafaba.

Taste scores ranged from 7.10 (C5) to 7.95 (C2), while flavour scores varied from 7.00 (C4) to 7.90 (C2). Higher aquafaba levels resulted in slightly lower taste scores, possibly due to the beany undertone of aquafaba.

Texture scores ranged from 6.30 to 7.60, with a decrease as aquafaba substitution increased. This could be attributed to the softer, less cohesive nature of cakes with higher aquafaba content, which may have resulted from its lower foam stability and higher moisture content.

Overall acceptability scores ranged from 6.75 (C5) to 7.85 (C2). Notably, the cake with 25% aquafaba substitution (C2) received a higher overall

Table 3. Texture properties of cake samples.

Percentage of aquafaba in cake	Hardness (N)	Resilience (%)	Springiness (%)	Adhesiveness (g/sec)	Cohesiveness (ratio)	Chewiness (N)	Gumminess
C1	20.03 ± 1.52^{a}	29.06 ± 1.21^{a}	89.82 ± 0.42^{a}	-8.84 ± 0.91^{c}	0.83 ± 0.02^{a}	15.44 ± 0.42^{a}	16.67 ± 0.42^{a}
C2	11.28 ± 0.22^{b}	28.22 ± 1.39^{a}	86.07 ± 3.09^{b}	-7.46 ± 1.45^{c}	0.76 ± 0.03^{b}	7.21 ± 0.47^{b}	8.59 ± 0.35^{b}
C3	10.84 ± 0.78^{b}	20.11 ± 2.25^{b}	69.55 ± 0.87^{c}	1.05 ± 0.28^{b}	0.52 ± 0.03^{c}	3.85 ± 0.58^{c}	5.64 ± 0.18^{c}
C4	5.93 ± 1.17^{c}	15.43 ± 1.08^{c}	32.78 ± 2.11^{d}	1.89 ± 0.01^{a}	0.41 ± 0.01^{d}	1.68 ± 0.02^{d}	2.08 ± 0.45^{d}
C5	5.05 ± 0.98^{c}	9.33 ± 0.71^{d}	31.39 ± 1.39^{d}	1.86 ± 0.01^{a}	0.78 ± 0.02^{b}	1.18 ± 0.01^{d}	4.59 ± 0.85^{c}

Means followed by different lowercase superscripts within similar column are significantly different ($p < 0.05$) according to Duncan's test. C1: 0% aquafaba + 100% egg; C2: 25% aquafaba + 75% egg; C3: 50% aquafaba + 50% egg; C4: 75% aquafaba + 25% egg; and C5: 100% aquafaba + 0% egg.

Table 4. Sensory properties of cake samples.

Sample	Crumb colour	Crust colour	Fluffiness	Appearance	Taste	Aftertaste	Flavour	Aroma	Texture	Overall acceptability
C1	8.0 ± 1.08^{a}	7.75 ± 0.9^{a}	6.55 ± 2.04^{a}	8.10 ± 1.02^{a}	7.75 ± 1.16^{a}	6.95 ± 1.64^{a}	7.75 ± 1.12^{a}	7.65 ± 0.88^{a}	7.24 ± 1.79^{ab}	7.75 ± 0.91^{ab}
C2	7.9 ± 1.07^{a}	7.85 ± 0.93^{a}	7.5 ± 0.89^{a}	7.85 ± 0.88^{a}	7.95 ± 0.99^{a}	7.4 ± 1.39^{a}	7.9 ± 1.28^{a}	7.5 ± 1.64^{a}	7.6 ± 1.05^{a}	7.85 ± 0.59^{a}
C3	7.15 ± 1.46^{ab}	6.85 ± 1.42^{ab}	6.75 ± 1.89^{a}	6.8 ± 1.58^{b}	7.65 ± 1.49^{a}	7.35 ± 1.46^{a}	7.4 ± 1.27^{a}	7.35 ± 1.69^{a}	6.3 ± 2.18^{b}	7.0 ± 1.34^{bc}
C4	6.55 ± 1.89^{b}	6.65 ± 1.89^{b}	7.15 ± 1.39^{a}	6.85 ± 1.53^{b}	7.45 ± 1.43^{a}	7.25 ± 1.41^{a}	7.0 ± 2.13^{a}	6.95 ± 1.70^{a}	6.95 ± 1.58^{ab}	7.0 ± 1.34^{bc}
C5	6.45 ± 2.16^{b}	6.50 ± 2.12^{b}	7.2 ± 1.47^{a}	6.55 ± 1.67^{b}	7.10 ± 1.41^{a}	7.30 ± 1.42^{a}	7.05 ± 1.57^{a}	6.95 ± 2.44^{a}	6.55 ± 2.06^{ab}	6.75 ± 1.59^{c}

Means followed by different lowercase superscripts within similar column are significantly different ($p < 0.05$) according to Duncan's test. C1: 0% aquafaba + 100% egg; C2: 25% aquafaba + 75% egg; C3: 50% aquafaba + 50% egg; C4: 75% aquafaba + 25% egg; and C5: 100% aquafaba + 0% egg.

acceptability score than the control (C1). Importantly, all samples scored above 6.0 (slightly liked) for overall acceptability, indicating that they were generally accepted.

Storage parameters of cake samples made with soybean aquafaba

Aquafaba substitution significantly ($p < 0.05$) affected the moisture content and water activity of the cake samples during storage, as shown in Table 5. Both parameters increased over eight days of storage period under ambient conditions. By the end of storage, C1 sample had the highest moisture content (13.88 ± 0.01%), while C4 sample had the lowest (12.04%). This increase in moisture content was likely due to moisture absorption from the surrounding environment. Similarly, water activity increased over time, with that of C3 sample increasing from 0.78 a_w to 0.80 a_w, indicating moisture uptake from the atmosphere.

Microbial analysis revealed that C5 sample had the lowest total viable count (TVC) throughout storage (1.07×10^1 - 2.50×10^6), while C1 sample had the highest (4.04×10^6) at the end of storage. Up to day 4, the TVC values remained within the World Health Organization's maximum permissible limit of 2.0×10^5 CFU/g (Gilbert *et al.,* 2000). No mould was detected on day 0, but by the end of storage, C1 sample had the highest yeast and mould count (YMC), whereas C5 sample had the lowest. The result suggests that aquafaba samples possesses significant antimicrobial properties compared to the control sample (C1), as higher egg substitution levels resulted in delayed mould development. Damian *et al.* (2018) reported that aquafaba contains saponins and phenolic compounds, which exhibit antimicrobial properties. After eight days of storage period, the YMC remained below the maximum permissible limit of 1.0×10^4 CFU/g (Gilbert *et al.,* 2000).

Table 5. Storage studies of cake samples.

Parameter	Day	C1	C2	C3	C4	C5
Moisture Content (%)	0	12.33 ± 0.21^{c}	18.09 ± 0.04^{a}	16.99 ± 0.11^{b}	10.14 ± 0.38^{e}	11.03 ± 0.33^{d}
	4	12.77 ± 0.04^{d}	17.29 ± 0.09^{a}	13.22 ± 0.02^{c}	13.04 ± 0.04^{d}	15.37 ± 0.08^{b}
	8	13.88 ± 0.01^{d}	16.75 ± 0.17^{c}	16.94 ± 0.09^{bc}	17.04 ± 0.07^{b}	17.88 ± 0.11^{a}
Water Activity (a_w)	0	0.79 ± 0.01^{d}	0.86 ± 0.00^{a}	0.78 ± 0.00^{e}	0.81 ± 0.00^{c}	0.83 ± 0.01^{b}
	4	0.82 ± 0.00^{c}	0.87 ± 0.01^{a}	0.79 ± 0.01^{d}	0.82 ± 0.01^{c}	0.84 ± 0.00^{b}
	8	0.84 ± 0.01^{b}	0.86 ± 0.00^{a}	0.80 ± 0.00^{c}	0.83 ± 0.01^{b}	0.84 ± 0.01^{b}
Total Viable Count (CFU/g)	0	1.05 × 101	1.90 × 101	1.00 × 101	3.10 × 101	1.00 × 101
	4	2.00 × 102	2.10 × 102	2.10 × 102	1.15 × 102	1.45 × 102
	8	4.04 × 106	3.4 × 106	3.8 × 106	2.85 × 106	2.50 × 106
Yeast and Mould Count (CFU/g)	0	ND	ND	ND	ND	ND
	4	0.2 × 101	0.1 × 101	ND	ND	ND
	8	0.45 × 101	0.30 × 101	0.10 × 101	0.20 × 101	0.15 × 101

Means followed by different lowercase superscripts within similar column are significantly different ($p < 0.05$) according to Duncan's test. C1: 0% aquafaba + 100% egg; C2: 25% aquafaba + 75% egg; C3: 50% aquafaba + 50% egg; C4: 75% aquafaba + 25% egg; and C5: 100% aquafaba + 0% egg.

Conclusion

The present work assessed the quality of cakes incorporating aquafaba as an egg substitute. Higher egg substitution levels resulted in increased baking loss and darker crust colour, while reducing the specific volume. Significant differences ($p < 0.05$) were observed in the proximate and textural properties of the cakes. Sensory evaluation indicated that sample C2, with a 25% egg substitution rate, was preferred over the control in terms of crust colour, fluffiness, taste, aftertaste, flavour, and texture. However, overall acceptability decreased with higher substitution levels, with C2 being the most accepted.

Aquafaba substitution significantly ($p < 0.05$) increased the moisture content and water activity of the cakes over time. Sample C2 was the most susceptible to microbial proliferation and spoilage, with the highest moisture content and water activity recorded on the eighth day of storage. Mould counts remained below the World Health Organization's maximum permissible limit of 1.0×10^4 CFU/g even after the eighth day of storage.

Overall, soybean aquafaba, produced by soaking soybeans for 16 h and cooking them for 6 h at a 1:4 bean-to-water ratio, proved to be a viable and acceptable egg alternative in cake production. Furthermore, cakes produced by substituting eggs with soybean aquafaba had an optimal shelf life of up to four days, and were found to be accepted.

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