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Development of Duckweed (*Lemna minor*)-Based Cracker with Enhanced Protein and Fibre Content

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Abstract

With the global shift towards health and sustainability, this study explores the potential of duckweed (*Lemna minor*) as a novel ingredient in high-protein, high-fibre crackers. Known for its rapid growth and rich nutritional profile, duckweed offers a promising solution to the rising demand for sustainable, plant-based proteins. This research evaluates the physicochemical properties of duckweed powder (DP), its incorporation at varying concentrations (2%, 4%, and 6%), and its impact on cracker quality. Key findings reveal that DP significantly enhances protein and fibre content without compromising sensory attributes. Crackers with DP exhibit improved moisture retention and shelf life, supporting their viability in health-oriented snacks. Proximate analysis shows DP had a remarkable amount of fibre (36.07%) and carbohydrates (52.43%). Incorporating DP increases moisture, protein, ash, crude fibre, and total dietary fibre in crackers. Functional properties, including water-holding (5.33 g/g) and oil-binding capacity (5.08 g/g), further highlight its benefits in food formulations. Sensory evaluation confirms that crackers with up to 6% DP maintain acceptable taste, texture, and overall appeal, with the 2% formulation receiving the highest acceptability score. This study underscores the potential of duckweed as a sustainable and nutritious food ingredient, offering an alternative protein source for the industry.

INTRODUCTION

The global food industry is increasingly focused on sustainable and nutritious alternatives to conventional protein sources. Rising concerns about climate change, health, and food security are driving the shift toward plant-based and environmentally friendly solutions. Duckweed (*Lemna minor*), a fast-growing aquatic plant, has emerged as a highly promising candidate due to its exceptional nutritional value, rapid growth, and minimal environmental footprint. Under optimal conditions—temperatures between 15° C and 30° C, abundant sunlight, and sufficient nutrients —, duckweed can double its biomass every 2–4 days [1]. Its cultivation requires no arable land and significantly less water compared to conventional crops, making it a sustainable solution to modern agricultural challenges.

Nutritionally, *Lemna minor* is dense and functional. It boasts a protein content of up to 45% on a dry-weight basis, which is significantly higher than that of many common grains and legumes, including soybeans and corn [2]. Its amino acid profile includes all essential amino acids, meeting World Health Organization (WHO) standards for human nutrition [3]. Notably, essential amino acids like leucine, isoleucine, and valine make up nearly half of the total essential amino acid composition, while non-essential amino acids like glutamic acid are present in abundance [4]. Furthermore, duckweed contains beneficial non-proteinogenic amino acids such as citrulline and taurine, which play unique roles in metabolic and cardiovascular health.

In addition to its protein profile, duckweed provides high levels of dietary fibre, with both soluble and insoluble forms derived from its cell wall, which is primarily composed of cellulose and hemicellulose [4]. These fibres contribute to digestive health, improved metabolism, and sustained satiety. Duckweed is also rich in bioactive compounds, including antioxidants like lutein and β-carotene, which are associated with reduced risks of chronic diseases [5]. These attributes

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collectively position duckweed as a functional, nutrient-dense ingredient with potential to combat protein deficiency and malnutrition, especially in regions facing food insecurity. International regulatory recognition further reinforces the potential of duckweed as a future food ingredient. The European Union approved *Wolffia arrhiza* and *Wolffia globosa* as traditional foods in 2015, with further approval in 2024 extending to protein concentrates from *Lemna gibba* and *Lemna minor* [6]. These endorsements not only validate duckweed's safety for human consumption but also highlight its viability as a sustainable alternative protein source, capable of producing 10 times more protein per hectare than soybeans.

Crackers, a globally popular, portable, and shelf-stable snack, offer an excellent platform for introducing duckweed to the food market. Traditional crackers are typically low in protein (7–8%) and often rely on refined wheat flour, which has limited nutritional value [7]. In response to growing consumer interest in health and wellness, there is an increasing demand for functional crackers that are high in protein, fibre, gluten-free, and low in fat [8]. Incorporating duckweed flour into crackers can enhance their nutritional quality while aligning with these emerging trends. For diabetics, protein-enriched snacks can help stabilize blood glucose levels by slowing carbohydrate absorption, while children benefit from increased protein intake, which is necessary for growth and development [9].

Research into duckweed-enriched crackers is still in its infancy. While preliminary studies suggest positive nutritional impacts, challenges remain in optimizing processing techniques, enhancing flavour profiles, improving texture, and ensuring product safety and acceptability. Prior investigations have explored functional ingredients such as whole-grain buckwheat, mucilage, and lentil extracts to enrich crackers [10], but few have examined integrating aquatic plants such as duckweed. Addressing these gaps could unlock new possibilities in functional food development. This study evaluates the physicochemical and sensory properties of duckweed-enriched crackers to assess their viability as a functional food. By exploring the application of *L. minor* in a familiar food product, this research aims to contribute to the growing body of knowledge on sustainable protein alternatives and support global efforts toward a healthier, more resilient food system.

MATERIALS AND METHODS

Raw materials

The ingredients for cracker production included wheat flour, butter, yeast, salt, and milk, purchased from local stores. Duckweed (*Lemna minor*) was sourced from Wong Aquaculture in Tuaran, Sabah, Malaysia.

Preparation of duckweed powder (DP)

Fresh duckweed (*L. minor) was rinsed with tap water to remove impurities, then dried in a cabinet dryer (Dryers FDD-1000) at 65* °C for 24 hours. The dried duckweed was ground into powder using a blender, sieved through a 68 µm mesh, and stored in an airtight container at 4° C.

Preparation of duckweed crackers

Four cracker formulations were prepared by replacing wheat flour with duckweed powder (0%, 2%, 4%, and 6%), labelled as F0 (control), F1, F2, and F3, respectively. The proportions of other ingredients (milk, salt, butter, yeast) remained constant. The total solids content was maintained at 100% across all formulations (**Table 1**). All ingredients were accurately weighed using an analytical balance. The dry ingredients (wheat flour, salt, yeast) were sieved and mixed. Butter and milk were whipped together for 5 minutes until smooth and fluffy. For duckweed crackers, the powder was blended with the dry ingredients before mixing with the wet ingredients. The dough was kneaded, rested for 1 h, then rolled to 0.5 cm thickness and cut into squares. The crackers were placed on parchment-lined trays and baked at 165° C for 20 min in an electric oven, then cooled for 15 min at room temperature.

Table 1. Formulation of cracker containing duckweed powder.

Ingredients (%)	Formulations F0 (Control)	F1	F2	F3
Wheat flour	61.5	59.5	57.5	55.5
Duckweed powder	0.0	2.0	4.0	6.0
Milk	16.4	16.4	16.4	16.4
Butter	20.5	20.5	20.5	20.5
Salt	0.8	0.8	0.8	0.8
Yeast	0.8	0.8	0.8	0.8
Total	100.0	100.0	100.0	100.0

Physicochemical analysis of duckweed powder

Water holding capacity

The WHC of duckweed powder was measured using a modified centrifugation method [7]. Briefly, 3 g of duckweed powder (W_1) was mixed with 30 mL of distilled water in a 50 mL centrifuge tube. After shaking for 30 s, the mixture was allowed to hydrate for 2 h at room temperature. The sample was then centrifuged at 2800 rpm for 10 min. The supernatant was discarded, and the remaining pellet was weighed (W_2). WHC was calculated as WHC = $[(W_2 - W_1)/W_1]$. The W_1 is the initial weight of duckweed powder; meanwhile, W_2 is the weight of duckweed powder and distilled water after centrifugation.

Oil binding capacity

The OBC of duckweed powder was measured using a centrifugation method. Briefly, 3 g of duckweed powder (W_1) was mixed with 30 mL of cooking oil in a 50 mL centrifuge tube. After shaking for 30 s, the mixture was left to stand for 2 h at room temperature. The sample was then centrifuged (5430R, Eppendorf, Germany) at 2800 rpm for 10 min. The supernatant was discarded, and the remaining pellet was weighed (W_2). OBC was calculated as OBC = $[(W_2 - W_1)/W_1]$. The W_1 is the initial weight of duckweed powder; meanwhile, the W_2 is the weight of duckweed powder and the cooking oil after centrifugation.

Swelling power

The swelling power of duckweed powder (DP) was determined following the method of Heong et al. [8] with modifications. Briefly, 0.3 g of DP was mixed with 7.5 mL of distilled water in a 50 mL measuring tube. The mixture was allowed to stand at room temperature for 24 h to ensure complete hydration and elimination of air bubbles. The final volume (mL) of the hydrated sample was recorded. Swelling power was calculated based on [(Volume of sample after hydration – Volume of sample before hydration)/Weight of dry sample].

Physicochemical analysis of the cracker

Texture analysis

The hardness of crackers was determined using a texture analyzer (TA-XT plus, Stable Micro Systems, UK). Samples were tested under standardized conditions: a 2 mm cylindrical probe compressed each cracker at 3 mm/s with a 5 kg load cell, traveling 4.0 mm at 20 ± 2° C. The maximum force (N) required to fracture the cracker was recorded as the hardness. Five replicates per formulation (including control) were analysed, with one measurement per individual cracker.

Colour analysis
The crackers' colour parameters (L*, a*, b*) were measured using a calibrated Chroma Meter CR-400 (Konica Minolta, USA). Samples (4g) were ground and filled to the 25 mm mark in sample cups. After white tile calibration, measurements were taken to assess lightness (L*), redness-greenness (a*), and yellowness-blueness (b*), with results displayed on the instrument screen.

Proximate analysis of duckweed powder and crackers
The nutritional composition of duckweed powder and crackers was analysed using standardized equipment and methods. Lipid content was determined via Soxhlet extraction (Soxtech Avanti 2050, Foss Analytical, Denmark), while protein content was measured using the Kjeldahl method (Kjeltech 2300 Analyzer, Foss Analytical, Denmark). Moisture content was assessed using a hot air oven, ash content with a muffle furnace, and crude fibre content with a FibreBag System (FibreTherm, Gerhardt Analytical Systems, Germany). Carbohydrate content was calculated by difference, subtracting the percentages of moisture, protein, lipid, ash, and crude fibre from 100%. All procedures followed official AOAC analytical methods.

Sensory evaluation
Fifty untrained panellists evaluated all cracker samples using a 9-point hedonic scale (1 = dislike extremely, 9 = like extremely). The assessment covered six attributes: colour, aroma, taste, texture (hardness), crispiness, aftertaste, and overall acceptability. The study followed a Randomized Complete Block Design (RCBD) with one-way treatment structure.

Monitoring of water activity
The shelf life of crackers containing varying duckweed concentrations was assessed by monitoring water activity (a_w) during storage. Samples were packaged in sealed bags and stored at ambient temperature (25° C). After 21 days, a_w measurements were performed in triplicate using a Hygrolab3 hygrometer (Rotronic, USA). Samples were placed in the measurement chamber, and readings were taken after securing the detector.

Statistical analysis
All data from physicochemical tests, proximate analysis, sensory evaluation, and shelf-life study will be analysed using one-way ANOVA in SPSS (v29.0), followed by Tukey's post-hoc test ($p<0.05$) to determine significant differences.

RESULT AND DISCUSSION

Physicochemical properties of duckweed powder

Water holding capacity, oil binding capacity, and swelling power of duckweed powder
The WHC, OBC, and SP of duckweed powder (DP) are influenced by its fibre, starch, and protein content. As shown in **Table 2**, DP has a WHC of 5.33 g/g, allowing it to retain over five times its weight in water. This high WHC is attributed to its rich soluble fibre content, which forms gels that trap water [11]. The polysaccharides in *L. minor*, such as heteromannans, xyloglucans, mixed-linkage glucans, and pectin, contribute to water retention and structural integrity. Pectin, the dominant soluble fibre, possesses strong gelation properties and may comprise up to 49% of the cell wall, enabling effective water absorption [12]. These characteristics support improved texture, mouthfeel, and shelf life in food applications. The OBC of DP is 5.08 g/g, making it effective for binding oils in food formulations, especially in plant-based meat alternatives and snacks. This is largely due to its soluble fibres, such as pectin, xyloglucans, and hemicelluloses, which provide structural integrity and functional benefits [13]. Hemicellulosic xylan also contributes to OBC, enhancing oil retention [13]. Additionally, duckweed proteins improve emulsification, ensuring better texture and flavour integration [14]. The SP of DP is 3.78 mL/g, reflecting its ability to absorb water and expand. Hemicelluloses and starch, which can make up 70% of *L. minor*, play a crucial role in this swelling behaviour [12,15]. Growth conditions such as nutrient availability and light exposure also influence the swelling capacity of duckweed [11].

Colour
The colour analysis of duckweed powder (DP) provides insights into its potential for food applications. In the CIELAB system, its colour parameters were L* (54.08), a* (-0.39), and b* (10.43) (**Table 3**). The L* value indicates moderate lightness, making DP visually appealing in food formulations [16]. Lighter-coloured food products are often associated with freshness and healthiness, qualities that may enhance the marketability of crackers containing duckweed powder [16]. The slight green hue (a* = -0.39) reflects its chlorophyll content, which contributes to antioxidant properties and nutritional benefits [17]. Chlorophyll levels vary with growth conditions, affecting colour intensity. Additionally, a strong yellow tone in DP (b* = 10.43) is due to carotenoids like lutein and β-carotene, which provide antioxidant benefits, support vision, and serve as precursors to vitamin A [18,19].

Table 2. WHC, OBC, and swelling power (dry weight basis) of duckweed powder (DP).

Sample	WHC (g/g)	OBC (g/g)	SP (mL/g)
DP	5.33 ± 0.12	5.08 ± 0.19	3.78 ± 0.29

Table 3. Colour analysis of duckweed powder (DP).

Sample	L*	a*	b*
DP	54.08 ± 0.12	-0.39 ± 0.01	10.43 ± 0.01

Proximate analysis of duckweed powder
The proximate analysis of duckweed powder (DP) (**Table 4**) provided insights into its nutritional profile. The moisture content of DP was measured at 7.45%, a level considered optimal for dry food storage and stability. Maintaining low moisture is crucial for minimizing microbial growth, extending shelf life, and preserving nutritional integrity [11]. Moreover, moisture influences the physical properties of powders as high moisture levels can compromise flowability and lead to lump formation, making the ingredient less suitable for uniform blending in dry food matrices [11]. Notably, the moisture content of duckweed can reach 95%, depending on environmental conditions and post-harvest processing techniques.

Moreover, the protein content of the DP sample was 17.02%, which falls within the reported range for *L. minor* (16%–29.7%) but remains considerably lower than values found in duckweed protein concentrates, which can reach up to 64%. Several factors, such as nutrient availability, light exposure during growth, harvest timing, and post-harvest treatment, can significantly influence protein accumulation and retention. Moreover, inadequate drying or over-processing may also lead to protein degradation. The ash content of the DP was 9.63%, aligning with reported values for duckweed species (7%–36%), and reflects its moderate mineral content [12]. Duckweed is generally a rich source of essential minerals such as calcium, magnesium, potassium, and iron. The fat content was measured at 2.65%, which is relatively low compared to certain duckweed strains, such as *Lemna gibba*, which can contain up to 9% fat [18]. The fats present in duckweed are predominantly polyunsaturated fatty acids (PUFAs), notably alpha-linolenic acid (ALA) and linoleic acid (LA), which contribute to cardiovascular health and anti-inflammatory benefits [20]. Although duckweed is relatively low in overall fat, the quality and composition of its lipids significantly enhance its nutritional value and utility in health-focused food products.

The carbohydrate content of DP was reported at 63.27%, aligning with the typical carbohydrate profile of duckweed species, which ranges from 40% to 60%. The carbohydrates in duckweed include starch, cellulose, hemicellulose, and pectin. Starch serves as a readily digestible energy source, while the non-starch polysaccharides contribute to dietary fibre content [21]. Moreover, the crude fibre content (36.07%) of the DP sample was comparatively high relative to standard *L. minor* values, which typically range from 5% to 15% [18]. Comprising cellulose, hemicellulose, and lignin, crude fibre plays a crucial role in supporting digestive health, improving bowel regularity, and promoting satiety [22].

Proximate composition of crackers incorporated with duckweed powder

Moisture content varied significantly (p<0.05), with the control (F0) showing the lowest value at 2.56%, while formulations F1 (5.81%), F2 (5.72%), and F3 (4.84%) exhibited higher moisture retention (**Table 5**). For dry products like crackers, a moisture content below 12% is ideal, as excess water can lead to spoilage, affect texture, and reduce shelf stability. Although no significant differences were found between F1 and F2 (p>0.05), the increased moisture can be attributed to the high protein and carbohydrate levels in duckweed powder (DP), which enhance water-binding capacity [23]. However, excessive DP might disrupt the dough structure, slightly reducing moisture retention [21].

Protein content showed a slight increase across formulations, from 8.91% in F0 to 9.55% (F1), 9.56% (F2), and 9.61% (F3), although the difference was not statistically significant (p>0.05). This modest rise is likely due to the naturally high protein concentration of duckweed (30–40% dry weight) [24]. Similar observations have been reported in other baked goods using plant-based protein sources [25,26], indicating that DP can enhance protein content even at low levels without affecting functional baking properties. Fat content slightly declined with the addition of DP, from 22.93% (F0) to 22.77% (F1), 22.69% (F2), and 22.36% (F3), though these changes were not statistically significant (p>0.05). The reduction stems from substituting wheat flour with low-fat duckweed powder (1–3% fat) [18]. Despite the decrease, fat levels remained within the optimal range, maintaining the desired cracker texture and flavour [23]. In terms of ash content, F3 showed a noticeable rise, aligning with duckweed's known mineral richness, including calcium, magnesium, and potassium [23]. This suggests DP contributes to mineral content and justifies further detailed mineral analysis [27].

Carbohydrate content decreased with DP incorporation: 44.31% (F0), 40.02% (F1), 39.39% (F2), and 39.57% (F3), with statistical significance (p<0.05). The reduction is primarily due to replacing carbohydrate-rich wheat flour with higher-protein, higher-fibre duckweed [28]. The slight increase in F3 over F2 may be due to variations in moisture content, which can affect calculations using the difference method [29]. Crude fibre content progressively increased with higher DP levels: 21.22% (F0), 21.81% (F1), 22.60% (F2), and 23.49% (F3). While F0 and F1 were not significantly different, F3 showed a significantly higher fibre content than F0 and F1 (p<0.05), but not F2. The increase reflects the rich dietary fibre content of duckweed, which promotes gut health and glycaemic control [18,27].

Physicochemical properties of crackers incorporated with duckweed powder

Hardness

As presented in **Table 6**, the mean hardness values for cracker formulations were F0 (411.00), F1 (1049.46), F2 (1052.95), and F3 (1093.79). A significant increase in hardness was observed with the addition of 2% duckweed powder (DP) (p<0.05), but no further significant changes were noted at 4% or 6%. The initial increase in hardness can be attributed to the partial replacement of wheat flour with DP, which disrupts gluten network formation and leads to a denser, firmer texture [30]. The high fibre content of DP also contributes to increased dough stiffness and moisture absorption, promoting earlier moisture loss during baking and resulting in a harder cracker [29,31].

Furthermore, protein-starch interactions and modifications in starch gelatinization likely reinforce the hardness of the product [32,33]. The plateau in hardness at higher concentrations (4% and 6%) suggests that the dough matrix may have reached a saturation point in its response to duckweed incorporation. At this stage, the structural effects of additional DP are likely masked by limitations in dough binding capacity or by a threshold beyond which further substitution no longer significantly alters the texture.

Table 4. Proximate composition (dry weight basis) of duckweed powder (DP).

Sample	Moisture (%)	Protein (%)	Fat (%)	Ash (%)	Carbohydrate (%)	Crude fiber (%)
DP	7.45 ± 0.07	17.02 ± 1.10	2.65 ± 0.11	9.63 ± 0.84	63.27 ± 0.98	36.07 ±0.67

Table 5. Proximate composition of crackers incorporated with duckweed powder (DP).

Sample	Moisture (%)	Protein (%)	Fat (%)	Ash (%)	Crude fibre (%)	Carbohydrate (%)
F0	2.56 ± 0.02[c]	8.91 ± 0.09[a]	22.93 ± 0.10[a]	0.07 ± 0.01[a]	21.22 ± 0.11[b]	44.31 ±0.09[a]
F1	5.81 ± 0.06[a]	9.55 ± 0.40[a]	22.77 ± 1.04[a]	0.05 ± 0.01[b]	21.81 ± 0.17[b]	40.02 ±1.65[b]
F2	5.72 ± 0.01[ab]	9.56 ± 0.19[a]	22.69 ± 0.04[a]	0.06 ± 0.02[ab]	22.60 ± 0.31[ab]	39.39 ±0.47[b]
F3	4.84 ± 0.06[b]	9.61 ± 0.13[a]	22.36 ± 0.01[a]	0.10 ±0.01[a]	23.49 ± 0.74[a]	39.57 ±0.62[b]

Note: *a-c Different letters in the same column are significantly different (p<0.05)
*F0 (control, 0% duckweed powder), F1 (2% duckweed powder), F2 (4% duckweed powder), and F3 (6% duckweed powder).

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Table 6. Texture analysis of crackers incorporated with duckweed powder (DP).

Sample of Cracker	Hardness
F0	411.00 ± 45.93[b]
F1	1049.46 ± 72.85[a]
F2	1052.95 ± 32.30[a]
F3	1093.79 ± 81.14[a]

Note: *[a-b] Different letters in the same column are significantly different ($p<0.05$)
*F0 (control, 0% duckweed powder), F1 (2% duckweed powder), F2 (4% duckweed powder), and F3 (6% duckweed powder).

Colour

Table 7 showed that the mean L* values, representing cracker lightness, decreased from 74.91 (F0) to 53.96 (F3) ($p<0.05$), with higher duckweed concentrations producing darker hues due to chlorophyll and carotenoids [29]. The a* values, indicating red-green shifts, declined from 6.64 (F0) to 1.98 (F3) ($p<0.05$), showing a transition toward a more neutral tone. While F1 differed significantly from F0, further duckweed increases had a smaller effect, consistent with research on plant-derived powders affecting food colour [34]. Similarly, b* values, representing yellowness, decreased from 26.43 (F0) to 16.29 (F3) ($p < 0.05$), as duckweed's chlorophyll content reduced yellow intensity [29]. These findings suggest that duckweed significantly alters cracker colour (**Fig. 1**), which may impact consumer appeal.

Table 7. Colour analysis of crackers incorporated with duckweed powder (DP).

Sample	L*	a*	b*
F0	74.91 ± 0.03[a]	6.64 ± 0.01[a]	26.43 ± 0.01[a]
F1	60.84 ± 0.01[b]	4.83 ± 0.02[b]	22.01 ± 0.01[b]
F2	58.85 ± 0.01[b]	2.34 ± 0.01[c]	19.53 ± 0.01[b]
F3	53.96 ± 0.02[c]	1.98 ± 0.02[c]	16.29 ± 0.01[c]

*[a-c] Different letters in the same column are significantly different ($p<0.05$)
*F0 (control, 0% duckweed powder), F1 (2% duckweed powder), F2 (4% duckweed powder), and F3 (6% duckweed powder).

Water activity

Water activity (a_w) represents the availability of free water in a food matrix and is a critical parameter influencing microbial stability and shelf life. As presented in **Table 8**, a significant reduction in a_w was observed only in the F3 formulation compared to the control (F0). This decrease may be attributed to the hygroscopic properties of duckweed, which enhance its capacity to bind free water at higher inclusion levels [21]. According to Aganduk et al. [35], the incorporation of plant powders at elevated concentrations can weaken the gluten network, diminishing its ability to retain gas and water molecules, thereby reducing a_w. The lack of significant differences in a_w between the F1 and F2 formulations suggests that lower levels of duckweed are insufficient to substantially alter the dough's water-binding characteristics. These results imply that a threshold concentration, such as 6% duckweed powder (DP), is required to exert a measurable effect on a_w. Interestingly, the data in **Table 8** indicate an increase in moisture content with duckweed incorporation, which appears contradictory to the observed reduction in a_w. However, as reported by Juarez-Enriquez et al. [36], moisture content and a_w are not linearly correlated. Water that is tightly bound to macromolecules, such as dietary fibre, contributes to the overall moisture content but does not significantly influence a_w.

Table 8. Water activity of crackers incorporated with duckweed powder (DP) after 21 days of storage.

Sample	a_w
F0	0.54 ± 0[a]
F1	0.53 ± 0[a]
F2	0.52 ± 0[ab]
F3	0.47 ± 0[b]

Note: *[a-b] Different letters in the same column are significantly different ($p<0.05$)
*F0 (control, 0% duckweed powder), F1 (2% duckweed powder), F2 (4% duckweed powder), and F3 (6% duckweed powder).

Sensory Analysis

Table 9 presents the hedonic scores for crackers incorporated with duckweed powder (DP). Although no statistically significant differences were observed in most sensory attributes among the cracker samples ($p>0.05$), a noticeable decrease in colour score was found at the highest level of DP (F3), indicating a perceptible change likely due to the natural pigments in duckweed. However, all values for colour, aroma, taste, texture, crispiness, aftertaste, and overall acceptance remained within an acceptable sensory range. The green color of the duckweed crackers was likely well received by panellists because it was perceived as natural. This aligns with previous findings, in which crackers containing green and blue spirulina were identified as green and blue, respectively.

Fig. 1. The appearance of crackers incorporated with duckweed.

Table 9. Sensory evaluation of crackers incorporated with duckweed powder (DP).

Sample	Colour	Aroma	Taste	Texture	Crispiness	Aftertaste	Overall acceptance
F0	6.48 ± 1.62[a]	6.66 ± 1.15[a]	6.24 ± 1.89[a]	6.86 ± 1.20[a]	6.68 ± 1.53[a]	6.62 ± 1.62[a]	6.58 ± 1.57[a]
F1	6.64 ± 1.48[a]	6.56 ± 1.30[a]	6.38 ± 1.81[a]	6.70 ± 1.47[a]	6.54 ± 1.67[a]	6.52 ± 1.66[a]	6.68 ± 1.60[a]
F2	6.42 ± 1.59[a]	6.46 ± 1.31[a]	5.96 ± 1.82[a]	6.74 ± 1.52[a]	6.56 ± 1.47[a]	6.00 ± 1.71[a]	6.35 ± 1.59[a]
F3	5.84 ± 1.87[b]	6.46 ± 1.54[a]	6.02 ± 1.62[a]	6.38 ± 1.68[a]	5.98 ± 1.80[a]	5.94 ± 1.58[a]	6.20 ± 1.46[a]

Note: *[a-b] Different letters in the same column are significantly different ($p<0.05$)
*F0 (control, 0% duckweed powder), F1 (2% duckweed powder), F2 (4% duckweed powder), and F3 (6% duckweed powder).

However, only the blue spirulina crackers were perceived as unnatural, while the green ones were considered more natural and acceptable [37]. The stability in aroma and taste suggests that DP, even at higher concentrations, does not introduce dominant or undesirable flavour profiles, or that such compounds are effectively masked by other ingredients. Likewise, the texture and aftertaste scores did not differ significantly, indicating the incorporation of duckweed did not adversely affect the eating experience. Overall, the results suggest that DP can be incorporated into cracker formulations without significantly compromising consumer acceptability, supporting its potential as a functional ingredient. Future studies could explore sensory optimization techniques to maintain or enhance palatability at higher inclusion rates.

CONCLUSION

This study evaluated the physicochemical properties of duckweed powder and its impact on the nutritional, sensory, and shelf-life attributes of crackers. Duckweed powder (DP) exhibited high water-holding (5.33 g/g) and oil-binding capacity (5.08 g/g), enhancing texture and flavour retention. Nutritionally, it is rich in fibre (36.07%) and carbohydrates (52.43%), making it a valuable functional ingredient. Thus, incorporating duckweed powder into crackers increased protein and fibre content. However, colour acceptability significantly declined at the highest inclusion level, which may affect overall consumer appeal despite stable scores for other sensory parameters. Additionally, reduced water activity in duckweed-enriched crackers suggests improved shelf life. Nevertheless, the current characterization of DP was limited to its functional properties and colour. Analyses including amino acid profile, fibre solubility, and lipid composition should be addressed in future research. Addressing these aspects will support the broader application of DP to develop nutritious, sustainable food products.

CONFLICT OF INTEREST

The authors have declared that no conflict of interest exists.

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