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Research Article

The Effect of Okra Seed (*Abelmoschus esculentus*) Powder Supplementation on Nutritional, Textural, Microstructural, and Sensory Properties of Gluten-Free Muffins

Altan Sahan and Ezgi Ozgoren Capraz

Department of Food Engineering, Pamukkale University, Denizli 20160, Türkiye

Correspondence should be addressed to Ezgi Ozgoren Capraz; ezgio@pau.edu.tr

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Celiac disease is an autoimmune-mediated systemic disorder that develops in those who are genetically predisposed, the management of which is limited to a lifelong gluten-free diet. Gluten-free foods contain fewer proteins, dietary fiber, and minerals than their gluten counterparts. Among the appropriate ingredients, okra seed is known for its high protein, fat, and dietary fiber content, its well-balanced amino acid composition, and its rich unsaturated fatty acid profile. In the present study, muffins were prepared with part of the rice flour substituted by okra seed powder (OSP) (15, 30, and 45%) and the nutritional, textural, microstructural, and sensory properties of the gluten-free muffins were evaluated. The most preferred formulation was determined using the integrated SWARA-TOPSIS multicriteria decision-making method, revealing the 30% OSP-added muffin to be the optimum alternative, with 2.43% ash, 28.01% fat, 10.0% protein, 7.39% total dietary fiber, and 49.75 mg GAE/100 g total phenolic content. In a mineral matter analysis, the Mg, P, K, Ca, Mn, Fe, and Zn contents of the 30% OSP-added sample were found to be 4.3, 1.2, 2.3, 2.7, 1.4, 4.9, and 2.0 times higher than the control sample, respectively. The OSP-added gluten-free muffin samples were also found to be an important source of essential and nonessential amino acids and a good source of linoleic and oleic acids. All of the muffin samples received acceptable sensory scores (>4/7). A texture profile analysis revealed that the hardness, adhesiveness, gumminess, and chewiness values of the muffins increased with the supplementation of OSP, while scanning electron microscope imaging revealed a homogeneous pore structure in the control samples that decreased as the OSP substitution rate increased. The results of the study revealed OSP to be an appropriate natural source of protein and dietary fiber in gluten-free muffin production.

1. Introduction

Celiac disease is an immune-mediated enteropathy affecting those who are genetically predisposed caused by gliadins—a subfraction of gluten found in wheat—and prolamins—their homologs—found in such cereals as rye and barley. Approximately 1 percent of the global population is known to be affected by the disease. When a person with celiac disease eats food containing gluten, chronic inflammation occurs in the small intestinal mucosa, leading to the destruction of the villi, a reduced absorption surface, and insufficient digestive enzymes, resulting in the malabsorption of iron, calcium, and vitamins A, D, E, and K. The only way to overcome the disease is through a lifelong gluten-free diet [1, 2]. Gluten-free cereal-based food formulations are poor sources of protein, minerals, and other nutritional components [3]. A previous study suggests that people who follow a gluten-free diet should be monitored for potential nutritional deficiencies [4]. In response to such recommendations, sources that are rich in protein, dietary fiber, minerals, or vitamins are preferred when developing new products.

Okra (*Abelmoschus esculentus*) is a tropical vegetable belonging to the *Malvaceae* family of plants that can be consumed fresh with its seeds although once ripened and dried, the seeds can be separated and replanted [5]. The seeds of the okra plant are its most nutritious components. They have been identified as excellent sources of fat and protein and have a well-balanced amino acid content. Okra seeds are a rich source of lysine amino acid, which is lacking in cereal products, while the 20–40 percent fat content of okra seeds is rich in unsaturated fatty acids, especially linoleic acid, which is important for human nutrition [6, 7]. Furthermore, phenolic compounds, including flavanol derivatives and oligomeric catechins, are abundant in okra seeds, the phenolic compound content of which makes them valuable antioxidants [8]. Finally, the seed husk is an excellent source of dietary fiber due to its high pectic polysaccharides and hemicellulosic polysaccharides content, which includes xyloglucan and glucuronoxylan [9].

Previous studies in the literature have tended to focus on the chemical composition of okra seed flour. In contrast, those investigating the use of seed flour in gluten-free products are rare. In the present study, protein-rich, gluten-free muffin formulations were produced with different proportions of the rice flour in the recipe (15%, 30%, and 45%) substituted by okra seed powder. The produced samples were subjected to proximate food composition (ash, fat, protein, moisture, soluble and insoluble dietary fiber, carbohydrate, and energy value), amino acid composition, fatty acid composition, mineral matter composition, antioxidant activity, phenolic content, and textural, microstructural, and sensory property analyses. Determining the optimum formulation is an important stage in developing gluten-free muffins. Multicriteria decision-making methods, such as SWARA and TOPSIS, facilitate the comprehensive evaluation of gluten-free muffin formulations based on multiple criteria rather than such a single criterion as sensory acceptability score. The okra seed-supplemented gluten-free muffin formulations applied in the present study were evaluated using the integrated SWARA-TOPSIS multicriteria decision-making method, in which the SWARA method is used to calculate the weights of the criteria for the evaluation of the formulations, and the TOPSIS method is used to rank the alternatives. The following steps were applied in the integrated SWARA-TOPSIS method for the determination of the optimum gluten-free muffin formulation: (i) construction of a decision-making team (comprising experts), (ii) identification of the selection criteria, (iii) structuring of the problem, (iv) gathering of expert evaluations for SWARA, (v) calculation of the criteria weights using SWARA, (vi) collection of evaluations of the formulations obtained from an experimental analysis based on the selected criteria, (vii) ranking of the alternative formulations using TOPSIS, and (viii) analysis and interpretation of the results [10].

2. Materials and Methods

2.1. Materials. The okra seeds for the study were purchased from a herbalist in Denizli, Türkiye. The seeds were ground in a laboratory-type blender (Waring Blender, Torrington, CT, USA) and sieved through a 500 μm sieve to produce a seed powder of standard particle size for use in the study.

The rice flour, eggs, sugar, corn oil, milk, and baking powder used to make the muffins were purchased from a local market in Denizli, Türkiye.

2.2. Preparation of Muffins. Table 1 presents the formulations of the muffins. The proportions of OSP included in the muffin formulations were determined based on the results of preliminary tests. The muffins were prepared according to the procedure described by Çelik and Isik [11] with some modifications. First, the eggs and sugar were whisked in a mixer (KMM060 Kitchen Chef, Kenwood) at high speed for 5 minutes, after which the corn oil and milk were added in the proportions stated in the formulations, and the whisking was continued at medium speed for 3 minutes. The remaining ingredients (okra seed powder (OSP), rice flour, and baking powder) were then added, and the final mixture was whisked at medium speed for 3 minutes to create the muffin batter. For the final stage, the muffin batter was transferred to cake pans in 35 g samples and baked in a 170°C oven (ASL Machine, Türkiye) for 25 minutes.

2.3. Proximate Composition Analysis. The moisture (method 934.01), protein (method 988.05), fat (method 954.02), and ash (method 942.05) analyses were carried out using the methods described by the AOAC [12].

The dietary fiber analysis was carried out using a Megazyme total dietary fiber assay kit (Wicklow, Ireland) following the AOAC 991.43 [13] and AACC 32-07 [14] methods.

The carbohydrate content (%) was calculated using the formula 100-(moisture + ash + fat + protein + total dietary fiber) [15], while energy values were calculated by multiplying the protein and carbohydrate contents by 4 kcal/g for each, multiplying the amount of fat by 9 kcal/g, and then summing the results. The resulting values are presented as kcal/100 g [16].

2.4. Mineral Matter Composition. The mineral matter composition analysis was conducted through ICP-MS (Perkin Elmer, NexION 2000, USA). A microwave-assisted digestion procedure was performed for the dissolution of the raw materials and the muffin samples. After the elements were ionized, they were transferred to the mass spectrometer and separated based on their mass-to-charge ratios, and the Mg, P, K, Ca, Mn, Fe, and Zn contents were subsequently determined in mg/kg [17].

2.5. Total Phenolic Content and Total Antioxidant Activity. Extracts were prepared from the raw materials and muffin samples to determine the total phenolic content and antioxidant activity values of the samples. The methodology defined by Ozgoren et al. [18] was used for the extract preparation, in which 1 g samples were weighed and homogenized with 10 mL of 70% aqueous methanol. After a 10-minute mixing process in an ultrasonic water bath (E 60 H Model, Elma Co., Germany) and 15 minutes in a mechanical shaker (WiseShake SHO-1D, Wertheim, Germany), the samples were centrifuged (NF 1200 R, Nuve, Türkiye) at 8500g for 20 minutes at 4°C, and the supernatant was transferred into amber bottles. The procedure was repeated

Table 1: Formulations of gluten-free muffins (g).

Ingredients	Control	15 OSP	30 OSP	45 OSP
Rice flour	94.50	80.33	66.20	51.98
Okra seed powder	—	14.17	28.30	42.52
Egg	73.80	73.80	73.80	73.80
Sugar	55.00	55.00	55.00	55.00
Corn oil	44.40	44.40	44.40	44.40
Milk	18.90	18.90	18.90	18.90
Baking powder	5.40	5.40	5.40	5.40

Control: muffin produced with 100% rice flour; 15 OSP: muffin produced with 15% of the rice flour substituted by OSP; 30 OSP: muffin produced with 30% of the rice flour substituted by OSP; 45 OSP: muffin produced with 45% of the rice flour substituted by OSP.

once more for the remaining residue at the bottom of the centrifuge tubes.

The total phenolic content was determined using the Folin–Ciocalteu (FC) method outlined by Singleton et al. [19], and the results were expressed as mg gallic acid equivalent (GAE)/100 g dry matter. The calibration curve equation related to the gallic acid standard was $y = 0.01035x + 0.01856$, with a confidence coefficient of $R^2 = 0.9994$.

Antioxidant activity was determined using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) method [20], and the results were expressed as μmol Trolox equivalent (TE)/100 g dry matter. For the Trolox standard, the calibration curve equation was determined as $y = -0.01855x + 1.04557$ with $R^2 = 0.9927$.

2.6. Techno-Functional Properties of Okra Seed Powder and Rice Flour. The water holding capacity (WHC), swelling volume (SV), and oil absorption capacity (OAC) of the samples were determined using the method described by Abebe et al. [21], and bulk density (BD) using the method applied by Ofori et al. [22].

2.7. Amino Acid Composition. A JASEM LC-MS/MS amino acid analysis kit (JASEM JSM-CL-508, Istanbul, Türkiye) was utilized for the determination of the amino acid composition of the samples, and the amino acid concentration was determined from electrospray ionization in multiple reaction monitoring modes. For the analysis, 0.5 g of the homogenized sample was weighed into glass tubes, after which 4 mL of JASEM amino acid reagent (JASEM JSM-CL-508, Istanbul, Türkiye) was added, and the mixture was hydrolyzed for 24 hours at 110°C. After 24 hours, the hydrolyzed sample was cooled to room temperature and centrifuged at 4000*g* for 5 minutes, and 100 μL of the supernatant was then extracted and diluted with water to achieve an 800-fold diluted hydrolysate. A 50 μL sample of the diluted hydrolysate was then placed in a vial, 50 μL of the internal standard mixture and 700 μL of the JASEM acidic hydrolysis solution were added, and the mixture was vortexed for 5 seconds. The prepared samples were then injected into the LC-MS/MS system. To determine the amino acid amounts, a calibration curve was generated as a 5-point calibration set in accordance with the kit manufacturer's instructions [23].

2.8. Fatty Acid Composition. The fatty acid composition of the samples was measured using the official AOCS [24] method. After the oil in the samples was separated using the Soxhlet extraction method, 0.2 g of each oil sample was weighed and 2 mL of n-hexane was added. Then, 200 μL of 2 N methanolic potassium hydroxide was added and vortexed, and the sample was allowed to stand for approximately 30 minutes to allow phase separation. A 1 μL sample was removed from the clear upper layer using a syringe and injected into a GC device (Agilent 7820A, Santa, USA) equipped with a flame ionization detector. The fatty acids were then separated using a capillary column (Agilent Technologies, USA), using hydrogen as the carrier gas.

2.9. Texture Profile Analysis. The texture profile analyses of the muffin samples were performed using a Brookfield CT3-4500 texture analyzer (Brookfield Eng. Lab. Inc., USA). The muffin samples were cut horizontally 20 mm from the base and the upper portion was discarded. Compression tests were carried out using a 3.81 cm diameter cylinder probe at 50% strain and with a trigger force of 4.5 g, with pretest and test speeds of 1 mm/s, and the hardness, adhesiveness, resilience, gumminess, and chewiness of the muffin samples were measured [25].

2.10. Microstructural Analysis. The muffins were cut into $3 \times 3 \times 3$ cm samples and then freeze-dried (Savant Modulyod-230, Thermo Electron Corporation, USA) for 12 h. The freeze-dried muffin samples were then coated with gold in a high-vacuum coating machine (Q 150R ES, Quorum Technologies Ltd., UK) for 500 seconds. The microstructures of the muffins were then visualized using a scanning electron microscope (FEI Quanta 250 FEG, Hillsboro, Oregon, USA).

2.11. Sensory Analysis. Each sample was randomly coded with a 3-digit number. After reaching room temperature, the muffins were presented to a total of 40 untrained panelists from Pamukkale University who were instructed to evaluate the muffins on a 7-point hedonic scale (1: extremely bad and 7: excellent) in terms of crust color, crumb color, odor, pore structure, texture, flavor, and overall acceptability [26]. All participants were informed about the study and provided written consent prior to their involvement in the sensory analysis.

2.12. Integrated SWARA-TOPSIS Method. Multicriteria decision-making (MCDM) methods are used to identify the best formulation and the optimum processing parameters for the food industry [27–30]. While various MCDM methods have been employed in the food sector, there have been few studies to date integrating the

SWARA (a stepwise weight assessment ratio analysis) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) approaches. In one such example, Martin [31] applied the Plithogenic SWARA-TOPSIS method for the selection of the optimum food processing technologies for case studies.

In the present study, the different gluten-free muffin formulations were evaluated using the integrated SWARA-TOPSIS method to identify the best formulation. The SWARA was conducted for the calculation of criteria weights, and three sensory (flavor, texture, crust, and color) and four functional (protein, total dietary fiber, monounsaturated fatty acid, and total essential amino acid) properties were selected as the assessment criteria, the weights of which were determined based on the opinions of seven experts from the Food Engineering Department of Pamukkale University. The assigned weights were then applied following the TOPSIS approach to determine the most preferred okra seed-supplemented gluten-free muffin formulation.

2.12.1. SWARA Method. The SWARA method is an MCDM approach that is used to determine the relative weights of different criteria based on expert opinion [32]. The ease of application of the SWARA method has led to it being successfully applied to various MCDM problems. The SWARA procedure can be defined as follows [32–34]:

Step 1: the problem is initially clearly defined. Expert(s) with appropriate knowledge and experience in the problem domain are then selected, and the set of criteria that will be used to address the defined decision-making problem is identified.

Step 2: the defined criteria are ranked in descending order by expert(s) according to their importance. The most important criterion is positioned in first place and the least important is in last place, while the remaining criteria are ranked sequentially based on their importance.

Step 3: beginning with the second-ranked criterion, the expert(s) specify the relative importance of criterion j in comparison with the previous criterion $(j-1)$ for each criterion. This value denotes the comparative importance of the average value (s_j) [32].

Step 4: coefficient k_j is determined using the following equation:

$$k_j = \begin{cases} 1, & j = 1, \\ s_j + 1, & j > 1. \end{cases} \quad (1)$$

Step 5: the recalculated weights q_j are determined using the following equation:

$$q_j = \begin{cases} 1, & j = 1, \\ \dfrac{q_{j-1}}{k_j}, & j > 1. \end{cases} \quad (2)$$

Step 6: the relative criteria weights are determined as given in the following equation, in which w_j represents the relative weight of criterion j.

$$w_j = \frac{q_j}{\sum_{k=1}^{n} q_k}. \quad (3)$$

2.12.2. TOPSIS Method. The TOPSIS method is a widely used MCDM approach that is designed to rank various alternatives based on an evaluation of their proximity to the ideal solution. For the application of TOPSIS, the weights of each criterion and the performance values of each alternative with respect to each criterion are required [35]. The TOPSIS procedure is as follows [36, 37]:

Step 1: the decision matrix (D) is constructed as shown in equation (4). For $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$, A_i denotes the i. alternative, X_j denotes the j. criterion, and x_{ij} represents the performance value of the i. alternative with respect to the j. criterion.

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} X_1 & X_1 & \cdots & X_n, \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \end{array}. \quad (4)$$

Step 2: the normalized decision matrix (R) is presented as given in equation (5). For $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$, the normalized values (r_{ij}) are computed using equation (6).

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}, \quad (5)$$

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \quad (6)$$

Step 3: the weighted normalized decision matrix (V) is presented as given in equation (7). For $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$, the weighted normalized value (v_{ij}) is calculated by multiplying the normalized value with the corresponding criterion weight given by equation (8), in which w_j is the weight of the j. criterion.

$$V = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{bmatrix}, \quad (7)$$

$$v_{ij} = w_j \times r_{ij}, \quad (8)$$

Step 4: the positive ideal solution (A^*) and negative ideal solution (A^-) are determined using (9) and (10), respectively. A^* denotes the best performance values and A^- denotes the worst performance values with respect to each criterion ($j = 1, 2, \ldots, n$) in the weighted normalized decision matrix, in which J corresponds to the benefit criteria and J' to the cost criteria.

$$A^* = \{v_1^*, v_2^*, \ldots, v_n^*\} = \left\{\left(\max_i v_{ij} | j \in J\right), \left(\min_i v_{ij} | j \in J'\right)\right\}, \tag{9}$$

$$A^- = \{v_1^-, v_2^-, \ldots, v_n^-\} = \left\{\left(\min_i v_{ij} | j \in J\right), \left(\max_i v_{ij} | j \in J'\right)\right\}, \tag{10}$$

Step 5: the distance of each alternative ($i = 1, 2, \ldots, m$) from the positive ideal solution and the negative ideal solution are calculated using equations (11) and (12), respectively.

$$S_i^* = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^*\right)^2}, \tag{11}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}, \tag{12}$$

Step 6: the closeness coefficient (C_i^*) of each alternative ($i = 1, 2, \ldots, m$) is calculated using equation (13). C_i^* takes a value between 0 and 1, with larger C_i^* values indicating a better performance of the alternative.

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^*} \quad 0 \leq C_i^* \leq 1. \tag{13}$$

2.13. Statistical Analysis. IBM SPSS Statistics (Version 26.0. Armonk, NY: IBM Corp.) was used for the statistical analysis. Significant differences among means were identified through Duncan's multiple range test ($p < 0.05$). All tests were performed at least in triplicate.

3. Results and Discussion

3.1. Chemical Properties of Rice Flour and Okra Seed Powder. Table 2 presents the results of the chemical composition analysis of the rice flour and OSP.

The chemical analysis results reveal the ash content of OSP to be around 12.9 times higher than that of rice flour, while the fat content, protein content, soluble dietary fiber content, and insoluble dietary fiber content were around 80 times, 4.2 times, 9.3 times, and 13.6 times higher, respectively. In contrast, the rice flour contained approximately 25 times more carbohydrates than the OSP. The analysis of the energy values of the raw materials revealed the energy value of OSP to be approximately 9% higher than that of rice flour.

Previous studies in the literature have reported OSP to have an ash content in the range of 3.42–7.80%, as well as 14.73–48.00% fat content, 16.80–44.3% protein content, 3.45–36.9% fiber content, and 6.69–36.83% carbohydrate content [6, 22, 38–41].

Okra seed powder is also reported to be higher in magnesium (Mg), phosphorus (P), potassium (K), calcium (Ca), manganese (Mn), iron (Fe), and zinc (Zn) than rice flour.

Previous studies in literature report the content of Mg in okra seeds to vary in the range of 126.5–8207.9 mg/kg, P in the range of 23.99–14970.0 mg/kg, K in the range of 344.2–15900.6 mg/kg, Ca in the range of 1.94–2023.1 mg/kg, Mn in the range of 2.49–117.1 mg/kg, Fe in the range of 32.2–324.49 mg/kg, and Zn in the range of 15.89–160.7 mg/kg [41–45].

Included in the health benefits of phenolic compounds that occur naturally in food is their antioxidant activity. Such compounds inhibit or slow the oxidation processes that arise from the free radicals in living cells, and in doing so, help protect against various disorders associated with oxidative stress [7]. The total phenolic content of OSP is reported to be approximately 4.9 times higher and antioxidant activity to be approximately 4.1 times higher than in rice flour. In the present study, the total phenolic content and antioxidant activity values of okra seed are quite similar to previous studies [39, 46, 47]. The small differences observed in the chemical composition of okra seeds may be attributable to the differences in variety, climatic conditions, and harvesting time [22, 45].

All of the abovementioned nutritional properties identify OSP as a valid alternative to rice flour for the enrichment of gluten-free products.

3.2. Techno-Functional Properties of Rice Flour and Okra Seed Powder. Table 3 presents some techno-functional properties of rice flour and OSP.

The SV was determined by dividing the total volume of the swollen sample by the dry weight of the sample [21]. The SVs of rice flour and OSP are 2.52 mL/g and 3.91 mL/g, respectively. The WHC of the rice flour and OSP, referring to the amount of water retained by the sample without subjecting it to any stress [21], are 1.78 g/g and 3.77 g/g,

Table 2: Chemical properties of the rice flour and OSP.

Parameters	Rice flour	Okra seed powder
Moisture (%)	7.58 ± 0.48	7.83 ± 0.05
Ash (%)*	0.50 ± 0.02	6.44 ± 0.29
Fat (%)*	0.36 ± 0.05	28.81 ± 0.36
Protein (%)*	7.28 ± 0.01	30.31 ± 0.12
Soluble dietary fiber (%)*	0.49 ± 0.10	4.57 ± 0.30
Insoluble dietary fiber (%)*	1.38 ± 0.20	18.79 ± 0.82
Total dietary fiber (%)*	1.87 ± 0.30	23.36 ± 1.12
Carbohydrate (%)*	82.42 ± 0.76	3.25 ± 1.70
Energy value (kcal/100 g)*	361.98 ± 3.47	393.51 ± 3.96
Mg (mg/kg)	322.3 ± 4.5	5237.8 ± 0.4
P (mg/kg)	1339.9 ± 0.8	10492.7 ± 1.0
K (mg/kg)	1357.9 ± 1.9	12735.2 ± 0.3
Ca (mg/kg)	4.9 ± 0.8	286.7 ± 0.6
Mn (mg/kg)	13.6 ± 1.2	29.2 ± 1.1
Fe (mg/kg)	3.4 ± 0.3	382.5 ± 1.5
Zn (mg/kg)	10.2 ± 2.9	68.9 ± 0.8
Total phenolic content (mg GAE/100 g)	23.96 ± 0.60	117.07 ± 3.47
Total antioxidant activity (μmol TE/100 g)	8.03 ± 0.07	33.06 ± 2.15

*In wet basis.

Table 3: Techno-functional properties of rice flour and OSP.

Parameters	Rice flour	Okra seed powder
SV (mL/g)	2.52 ± 0.18	3.91 ± 0.14
WHC (g/g)	1.78 ± 0.07	3.77 ± 0.20
BD (g/mL)	0.79 ± 0.01	0.63 ± 0.03
OAC (g/g)	0.93 ± 0.04	0.97 ± 0.02

SV: swelling volume, WHC: water holding capacity, BD: bulk density, OAC: oil absorption capacity.

respectively. The differences in these results may be related to the higher dietary fiber content of OSP when compared to rice flour (Table 2). Sahan et al. [48] reported that dietary fiber contributes to the hydration properties attributed to the hydroxyl groups in the fiber structure allowing more water interactions through hydrogen bonding. These SV and WHC content results are in close agreement with Abebe et al. [21] who reported the SV and WHC values of rice flour to be 2.58 mL/g and 1.78 g/g, respectively.

BD is important for determining packaging requirements [44]. The BD value of OSP is lower than that of rice flour, which may be attributable to the particle size of the flour. Siliveru et al. [49] reported BD to be related to the particle size and moisture content of the flour. Similar results have been reported previously, with a BD of 0.57 g/mL for OSP reported by Omoniyi et al. [44], while in another study [50], the BD of rice flour was determined as 0.65 g/mL.

Du et al. [51] stated that OAC is important for improving the mouth feel and flavor of food products. Mitharwal and Chauhan [52] noted that OAC is influenced by several factors, such as the quality of proteins, the proportion of hydrophobic to hydrophilic amino acids, and the structural arrangement of the proteins. The OAC of OSP was determined approximately 4.3% higher than that of rice flour. Kaushal et al. [50] reported the OAC of rice flour to be 1.12 g/g. In another study, OAC detected in six rice flour cultivars ranged between 0.60 and 0.73 g/g [53].

In another study, techno-functional properties of several legume flours were investigated, reporting bulk densities ranging from 0.543 g/mL (black bean) to 0.816 g/mL (lentil) and oil absorption capacities from 0.93 g/g (lentil) to 1.38 g/g (black bean) [51].

3.3. Proximate Composition of the Muffin Samples. Table 4 presents the proximate composition of the gluten-free muffin samples. The addition of greater proportions of OSP led to increases in the ash, fat, protein, and soluble and insoluble dietary fiber content ($p < 0.05$), while carbohydrate values decreased ($p < 0.05$) and the moisture content and energy values of the muffin samples were statistically similar ($p > 0.05$).

Fats are key components of human nutrition and are the most energy-dense of the macronutrients [54]. The fat content of the 15%, 30%, and 45% OSP samples were approximately 9%, 17%, and 22% higher, respectively, than that of the control sample.

Ash is the term for the inorganic residue that remains after the removal of organic matter after burning food at high temperatures [55]. The ash content of the muffins varied between 1.76% and 2.7% and increased significantly ($p < 0.05$) as the OSP substitution rate increased. Food products with a high ash content are considered to be rich in mineral matter [56]. The results of the mineral matter analysis in the present study revealed that the amounts of Mg, P, K, Ca, and Fe increased proportionally as the OSP substitution rates were increased in the muffin formulation ($p < 0.05$). While no difference ($p > 0.05$) was noted in the Zn content of the control and 15% OSP substituted muffins, these muffins contained lower ($p < 0.05$) amounts of Zn than other muffins (30% and 45% OSP), while the difference between the Mn levels of the samples was insignificant ($p > 0.05$). The recommended daily intake of Mg, P, K, Ca, Mn, Fe, and Zn for adults is 420 mg, 1250 mg, 4700 mg, 1300 mg, 2.3 mg, 18 mg, and 11 mg, respectively. In

Table 4: Proximate composition of the muffin samples.

Parameters	Control	15 OSP	30 OSP	45 OSP
Moisture (%)	12.54 ± 0.23^{a}	12.32 ± 0.56^{a}	12.66 ± 1.05^{a}	12.73 ± 0.53^{a}
Ash (%)*	1.76 ± 0.02^{d}	2.06 ± 0.01^{c}	2.43 ± 0.13^{b}	2.73 ± 0.10^{a}
Fat (%)*	23.97 ± 0.34^{c}	26.19 ± 0.81^{b}	28.01 ± 0.12^{a}	29.16 ± 0.01^{a}
Protein (%)*	7.36 ± 0.41^{d}	8.70 ± 0.09^{c}	10.00 ± 0.15^{b}	11.43 ± 0.15^{a}
Soluble dietary fiber (%)*	0.98 ± 0.03^{c}	1.48 ± 0.01^{b}	1.96 ± 0.06^{a}	2.14 ± 0.23^{a}
Insoluble dietary fiber (%)*	1.84 ± 0.11^{b}	3.30 ± 0.47^{b}	5.43 ± 0.76^{a}	6.72 ± 0.89^{a}
Total dietary fiber (%)*	2.82 ± 0.13^{c}	4.77 ± 0.47^{b}	7.39 ± 0.71^{a}	8.86 ± 0.66^{a}
Carbohydrate (%)*	51.55 ± 0.86^{a}	45.96 ± 1.76^{b}	39.50 ± 0.18^{c}	35.08 ± 1.45^{d}
Energy value (kcal/100 g)*	451.46 ± 1.24^{a}	454.38 ± 0.06^{a}	450.16 ± 0.25^{a}	448.51 ± 5.24^{a}
Mg (mg/kg)	175.1 ± 0.7^{d}	441.6 ± 1.8^{c}	745.7 ± 1.2^{b}	1037.1 ± 2.8^{a}
P (mg/kg)	3977.2 ± 2.8^{d}	4301.6 ± 0.9^{c}	4891.4 ± 1.5^{b}	5398.0 ± 2.1^{a}
K (mg/kg)	1034.6 ± 2.8^{d}	1632.8 ± 1.6^{c}	2340.1 ± 2.5^{b}	3059.0 ± 1.6^{a}
Ca (mg/kg)	20.3 ± 2.8^{d}	36.6 ± 2.1^{c}	54.2 ± 2.9^{b}	70.6 ± 2.2^{a}
Mn (mg/kg)	4.9 ± 1.1^{a}	6.0 ± 1.2^{a}	7.0 ± 1.4^{a}	8.3 ± 1.7^{a}
Fe (mg/kg)	9.0 ± 2.5^{d}	25.6 ± 1.8^{c}	43.8 ± 1.9^{b}	63.7 ± 2.3^{a}
Zn (mg/kg)	7.3 ± 0.8^{c}	10.1 ± 2.2^{c}	14.5 ± 1.0^{b}	18.8 ± 0.8^{a}
Total phenolic content (mg GAE/100 g)	32.91 ± 0.96^{c}	35.41 ± 1.58^{c}	49.75 ± 0.18^{b}	55.51 ± 0.23^{a}
Total antioxidant activity (μmol TE/100 g)	12.85 ± 0.63^{c}	14.53 ± 0.33^{b}	$15.45 \pm 0.15a^{b}$	16.23 ± 0.01^{a}

Different superscript letters in rows denote statistical differences ($p < 0.05$). *In wet basis.

this regard, the consumption of 100 g of the control sample was found to provide 4.14%, 31.82%, 2.20%, 0.16%, 21.20%, 5%, and 6.64% of the recommended daily intake, while consuming 100 g of the 45% OSP muffin sample provided 24.69%, 43.18%, 6.51%, 0.54%, 36.09%, 35.59%, and 17.09%, respectively.

Plant protein can serve as an alternative to animal protein for consumers living in low-income countries, as well as for vegetarians or those with special dietary requirements [40]. The protein content of the control sample was 7.36%, compared to 11.43% in the sample with the highest OSP content (45%), and protein content was found to increase significantly as the OSP substitution rate was increased ($p < 0.05$).

Dietary fiber has been reported to reduce the risk of diabetes, coronary heart disease, gastrointestinal disorders, and obesity [25]. The recommended dietary fiber intake (RDI) for adults is 28 grams per day [57], based on which, consuming 1 portion (100 g) of the 15%, 30%, and 45% OSP muffins provided 17.04%, 26.39%, and 31.64% of the recommended daily dietary fiber intake, respectively, while the control sample provided only 10.07%.

Epidemiological studies have shown that the consumption of foods that are rich in phenolic compounds reduces the risk of neurodegenerative diseases, cardiovascular diseases, and certain types of cancer [58]. The total phenolic content and antioxidant activity of the muffins increased as the OSP substitution rate increased, with the addition of 45% OSP to the muffin formulation increasing the total phenolic content by approximately 1.7 times and the antioxidant activity value by approximately 1.3 times when compared to the control sample.

The changes in the composition of the enriched muffin samples were found to be related to the nutritional characteristics of the raw materials (OSP and rice flour).

In a previous study reporting the supplementation of wheat flour with okra flour in biscuits, adding 25% okra flour to the formulation was found to increase the ash content of the biscuits by around 5 times, the protein content by around 2 times, and the dietary fiber content by around 4 times when compared to the control sample [59]. In another study, Omoniyi et al. [44] added different proportions (4, 8, 12, 16, and 20 grams) of OSP to soup and found that the addition of the highest amount of OSP (20 grams) to the formulation increased the protein, ash, fat, and fiber content of the soup by approximately 55%, 9%, 42%, 42%, and 222%, respectively, when compared to the soup containing no OSP (control sample).

3.4. Amino Acid Composition.

Amino acids are cell-signaling molecules, regulators of gene expression and protein phosphorylation cascades, and are key precursors to the synthesis of hormones and low-molecular weight nitrogenous substances [60]. Table 5 presents the amino acid composition of the raw materials and the muffin samples.

OSP was found to contain approximately 3.2 times more essential amino acids and 3.8 times more nonessential amino acids than rice flour, with leucine identified as the most abundant essential amino acid in OSP, followed by lysine and phenylalanine, concurring with the findings of previous studies in the literature [5, 41]. It has been reported that the essential amino acid content of food plays an important role in the determination of protein quality [61].

The amino acid analysis of the muffin samples revealed that as the ratio of OSP in the muffin formulation was increased, so did the quantities of all essential and nonessential amino acids ($p < 0.05$). A comparison of essential amino acid levels revealed approximate increases of 41.5% in leucine, 28.2% in lysine and 15.1% in phenylalanine when compared to the control sample upon the addition of 45% OSP to the formulation. An inadequate intake of essential amino acids can lead to such adverse effects as malabsorption of organic and inorganic compounds, decreased neurotransmitter synthesis, loss of appetite, vomiting, emotional disorders (moodiness, depression, and anxiety), insomnia, irritability, and anemia [62].

Table 5: Amino acid composition of the raw materials and muffin samples (mg/100 g).

Amino acids	Rice flour	OSP	Control	15 OSP	30 OSP	45 OSP
Lysine	524.12 ± 0.09	1894.40 ± 4.98	579.77 ± 0.37^{d}	630.24 ± 0.52^{c}	679.06 ± 0.67^{b}	743.25 ± 0.64^{a}
Valine	390.99 ± 0.28	1386.11 ± 3.08	398.04 ± 0.24^{d}	414.39 ± 0.93^{c}	534.63 ± 0.18^{b}	604.61 ± 0.49^{a}
Methionine	134.67 ± 2.49	394.24 ± 0.22	160.25 ± 0.95^{d}	171.79 ± 0.35^{c}	190.50 ± 1.17^{b}	204.63 ± 0.89^{a}
Isoleucine	278.66 ± 0.06	727.05 ± 0.35	291.19 ± 0.58^{c}	299.87 ± 0.76^{c}	365.99 ± 1.24^{b}	383.94 ± 7.84^{a}
Leucine	647.11 ± 11.60	1955.02 ± 6.88	624.89 ± 3.54^{d}	636.92 ± 6.11^{c}	805.46 ± 4.13^{b}	884.45 ± 1.99^{a}
Phenylalanine	567.76 ± 0.11	1468.66 ± 28.18	577.71 ± 4.31^{d}	602.92 ± 4.57^{c}	653.56 ± 1.61^{b}	665.01 ± 4.32^{a}
Threonine	368.32 ± 6.53	1136.54 ± 6.15	404.21 ± 0.14^{d}	431.27 ± 1.54^{c}	447.77 ± 1.45^{b}	494.98 ± 0.03^{a}
Histidine	168.28 ± 0.62	874.82 ± 0.60	182.55 ± 2.47^{d}	228.87 ± 0.54^{c}	283.67 ± 0.10^{b}	301.41 ± 0.34^{a}
Total EAA	3079.91	9836.84	3218.61	3416.27	3960.64	4282.28
Serine	667.69 ± 0.01	1795.84 ± 3.37	696.26 ± 0.25^{d}	753.11 ± 0.13^{c}	829.73 ± 0.09^{b}	928.79 ± 0.19^{a}
Proline	676.61 ± 1.47	1522.17 ± 0.78	656.87 ± 0.21^{d}	682.07 ± 0.52^{c}	762.06 ± 0.06^{b}	781.06 ± 0.48^{a}
Alanine	964.52 ± 4.80	1831.19 ± 3.25	902.07 ± 2.74^{d}	956.55 ± 3.77^{c}	1048.00 ± 3.25^{b}	1071.04 ± 2.52^{a}
Tyrosine	417.31 ± 1.37	1055.24 ± 0.78	467.37 ± 2.48^{b}	477.22 ± 17.05^{b}	516.91 ± 0.40^{a}	531.39 ± 0.23^{a}
Aspartic acid	722.89 ± 1.33	4585.00 ± 10.95	820.78 ± 0.18^{d}	865.97 ± 0.21^{c}	1167.07 ± 2.26^{b}	1265.18 ± 1.34^{a}
Glutamic acid	1337.72 ± 1.22	6788.48 ± 6.44	1029.54 ± 2.03^{d}	1318.67 ± 0.32^{c}	1667.34 ± 3.00^{b}	1739.37 ± 2.80^{a}
Arginine	608.94 ± 0.26	2896.63 ± 1.25	560.81 ± 0.10^{d}	665.51 ± 0.08^{c}	793.55 ± 0.16^{b}	893.06 ± 0.16^{a}
Total NEAA	5395.68	20474.55	5133.70	5719.10	6784.66	7209.89

EAA: essential amino acids, NEAA: nonessential amino acids. Different superscript letters in rows denote statistical differences ($p < 0.05$).

A comparison of the nonessential amino acid content of the muffin samples revealed the glutamic acid content to be approximately 68.9% higher, alanine to be approximately 18.7% higher, and aspartic acid to be approximately 54.1% higher in the sample with 45% OSP when compared to the control sample.

3.5. *Fatty Acid Composition.*

An analysis of the fatty acid composition of a fat sample reveals its physical properties, stability, and nutritional value [63]. Table 6 shows the fatty acid composition of the raw materials and the muffin samples.

An analysis of the fatty acid content of the OSP revealed the most prominent fatty acids to be linoleic acid, palmitic acid, and oleic acid, respectively. Previous studies in literature have reported linoleic acid content of OSP in the range of 27.74–49.54%, palmitic acid content in the range of 17.05–31.56%, and oleic acid content in the range of 16.81–27.49% [39, 40, 47, 63].

In the present study, the most abundant fatty acids in the rice flour were linoleic acid (40.99%), oleic acid (36.23%), and palmitic acid (17.06%), while previous studies have reported linoleic acid (28.61–42.11%), oleic acid (35.86–44.68%), and palmitic acid (15.79–20.06%) to be the most abundant fatty acids in rice flour [64, 65]. The ratios of the most abundant fatty acids in OSP and rice flour measured in the presented study were consistent with those reported in the literature.

All of the muffin samples were found to be rich in polyunsaturated fatty acids (48.92–47.50%), with linoleic acid, oleic acid, and palmitic acid being the most prominent. Clinical evidence suggests that a high dietary intake of linoleic acid reduces the risk of cardiometabolic disease [66].

It was observed that the utilization of approximately 44% corn oil in the formulations of the muffin samples also affected the fatty acid composition of the products. An analysis of the fatty acid composition of the corn oil used in the study revealed the most prominent fatty acids to be linoleic acid (53.26%), oleic acid (31.21%), and palmitic acid (11.82%).

3.6. *Textural Properties.*

Table 7 shows the textural properties of the muffin samples. The replacement of rice flour with OSP gave the muffins a harder texture, related to the density of the muffin samples, due to the higher dietary fiber content, and the hardness values of muffin samples increased significantly from 1700.63 g (control) to 4316.38 g (45OSP), similar to the reported by Kaur and Kaur [67] in their study of flaxseed-enriched muffins. It has been reported that the harder texture of fiber-enriched muffins may be attributed to the dilution of gluten upon the addition of the fiber fraction [68].

Adhesiveness is measured as the negative work between two cycles [69], and the adhesiveness values of the muffin samples increased with the addition of 30% and 45% OSP to the muffin formulation ($p < 0.05$).

Resiliency is the ratio of recoverable energy after the removal of the initial compression [70]. The resilience values of all the muffin samples in the present study were found to be similar ($p > 0.05$). Gumminess is calculated by multiplying the hardness value with the cohesiveness value [25], while chewiness is calculated by multiplying the gumminess and springiness values and refers to the amount of energy needed to disintegrate the food for swallowing [71]. The gumminess and chewiness values increased with the addition of OSP to the muffin formulation in the present study. Mildner-Szkudlarz et al. [68] reported an increase in the gumminess and chewiness values of muffins enriched with raspberry and cranberry pomaces.

3.7. *Microstructural Properties.*

Figure 1 shows the scanning electron microscopy (SEM) images and photographs of the muffin samples.

Table 6: Fatty acid composition of the raw materials and muffin samples (%).

Fatty acids	Rice flour	OSP	Control	15 OSP	30 OSP	45 OSP
Lauric acid (C12 : 0)	0.01 ± 0.01	0.01 ± 0.01	0.04 ± 0.01^{a}	0.04 ± 0.01^{a}	0.03 ± 0.01^{a}	0.03 ± 0.01^{a}
Myristic acid (C14 : 0)	0.34 ± 0.01	0.27 ± 0.01	0.20 ± 0.01^{a}	0.21 ± 0.01^{a}	0.20 ± 0.01^{a}	0.20 ± 0.01^{a}
Palmitic acid (C16 : 0)	17.06 ± 0.02	30.53 ± 0.41	13.68 ± 0.24^{d}	14.69 ± 0.13^{c}	15.38 ± 0.05^{b}	16.14 ± 0.05^{a}
Palmitoleic acid (C16 : 1)	0.15 ± 0.01	0.44 ± 0.01	0.53 ± 0.03^{a}	0.47 ± 0.01^{a}	0.43 ± 0.01^{a}	0.42 ± 0.07^{a}
Stearic acid (C18 : 0)	1.76 ± 0.03	4.84 ± 0.01	2.90 ± 0.19^{a}	3.12 ± 0.01^{a}	3.13 ± 0.02^{a}	3.11 ± 0.03^{a}
Oleic acid (C18 : 1)	36.23 ± 0.01	24.34 ± 0.12	32.93 ± 0.17^{a}	32.32 ± 0.01^{b}	31.72 ± 0.08^{c}	31.32 ± 0.10^{d}
Linoleic acid (C18 : 2)	40.99 ± 0.04	34.77 ± 0.22	48.37 ± 0.56^{a}	47.75 ± 0.16^{ab}	47.55 ± 0.04^{ab}	47.20 ± 0.04^{b}
α-linolenic acid (C18 : 3)	1.30 ± 0.01	1.36 ± 0.01	0.55 ± 0.08^{a}	0.42 ± 0.01^{ab}	0.43 ± 0.09^{ab}	0.30 ± 0.03^{b}
Arachidic acid (C20 : 0)	0.58 ± 0.01	0.63 ± 0.01	0.39 ± 0.01^{b}	0.43 ± 0.01^{a}	0.44 ± 0.02^{a}	0.44 ± 0.01^{a}
Gadoleic acid (C20 : 1)	0.49 ± 0.01	ND	0.25 ± 0.03^{a}	0.23 ± 0.01^{a}	0.21 ± 0.02^{a}	0.21 ± 0.01^{a}
Behenic acid (C22 : 0)	0.63 ± 0.06	0.32 ± 0.01	0.17 ± 0.01^{a}	0.19 ± 0.01^{a}	0.20 ± 0.02^{a}	0.21 ± 0.03^{a}
Erucic acid (C22 : 1)	0.47 ± 0.01	2.49 ± 0.05	ND	0.15 ± 0.02^{c}	0.28 ± 0.01^{b}	0.42 ± 0.01^{a}
Total SAT	20.38	36.60	17.38	18.68	19.38	20.13
Total MUFA	37.34	27.27	33.71	33.17	32.64	32.37
Total PUFA	42.29	36.13	48.92	48.17	47.98	47.50

Total SAT: total saturated fatty acids; Total MUFA: total monounsaturated fatty acids; Total PUFA: total polyunsaturated fatty acids, ND: not detected. Different superscript letters in rows denote statistical differences ($p < 0.05$).

Table 7: Textural properties of the muffin samples.

Parameters	Control	15 OSP	30 OSP	45 OSP
Hardness (g)	1700.63 ± 19.62^{d}	2222.75 ± 49.14^{c}	3040.13 ± 22.10^{b}	4316.38 ± 6.19^{a}
Adhesiveness (mj)	0.01 ± 0.01^{c}	0.03 ± 0.01^{c}	0.13 ± 0.01^{b}	0.29 ± 0.05^{a}
Resilience	0.15 ± 0.01^{a}	0.14 ± 0.02^{a}	0.14 ± 0.01^{a}	0.13 ± 0.02^{a}
Gumminess (g)	788.95 ± 92.35^{c}	1025.55 ± 155.63^{c}	1554.25 ± 33.59^{b}	2381.48 ± 297.23^{a}
Chewiness (mj)	96.63 ± 14.77^{c}	118.31 ± 29.73^{c}	187.04 ± 4.64^{b}	284.00 ± 32.95^{a}

Different superscript letters in rows denote statistical differences ($p < 0.05$).

The SEM image of the control muffin sample reveals the air holes to be more homogenous than in the enriched samples, and the diameter of the air holes was noted to decrease with the addition of the OSP to the muffin formulation. Similar changes were also observed in the photographs of the muffin samples. The decrease in porosity of the muffins in which the rice flour content was partially substituted was thought to be related to the increase in the dietary fiber content of the muffins, which leads to a decrease in viscoelastic behavior, resulting thereby in the less entrapment of air bubbles [72]. This decrease in air bubbles also supports the increase in textural hardness associated with OSP substitution (Table 7).

Çelik and Isik [11] reported similar results in their study, in which it was determined that the cakes developed a more uneven surface and smaller pores as the watermelon rind powder substitution increased. In another study, black rice-based gluten-free muffins were enriched with amaranth flour, and a microstructure analysis of the muffin samples revealed reduced pore size that was attributable to the addition of the amaranth flour, which the authors explained was associated with the increase in the fiber content [72].

3.8. Sensory Properties. A sensory analysis is a scientific measurement of the responses of the senses of touch, taste, smell, sight, or hearing to different properties of food [26]. Figure 2 presents the results of the sensory analysis of the muffin samples. While the control sample received the highest score in all properties, the analysis scores of all the samples were higher than 4.00, being the midpoint of the 7-point hedonic scale. The 45% OSP content sample recorded the lowest scores for crust and crumb color, flavor, and overall acceptability ($p < 0.05$).

In an earlier study, Hu et al. [47] enriched gluten-free cookies with OSP at 2%, 4%, and 6% concentrations, and reported lower color scores for the enriched samples when compared to the control sample, while the texture, flavor taste, and overall acceptability scores were similar.

In a similar study by Akoja and Coker [59], the researchers prepared biscuits in which wheat flour was replaced with okra powder at different ratios (5%, 10%, 15%, 20%, and 25%) and reported that the control sample received the highest scores in all parameters (appearance, flavor, aroma, texture crunchiness, and overall acceptability) but that the panelists liked all of the samples in terms of their sensory properties, leading the researchers to conclude that up to 25% of okra flour could be added to the formulation.

3.9. SWARA-TOPSIS Application. The functional and sensory properties of the muffins in the present study were both significantly affected by the proportion of OSP in the formulation, which made the assessment of the optimum OSP level difficult as different criteria must be taken into account. The SWARA-TOPSIS integrated multicriteria decision-making method was selected for the selection of the optimum OSP level in the muffin formulation, and Table 8 shows

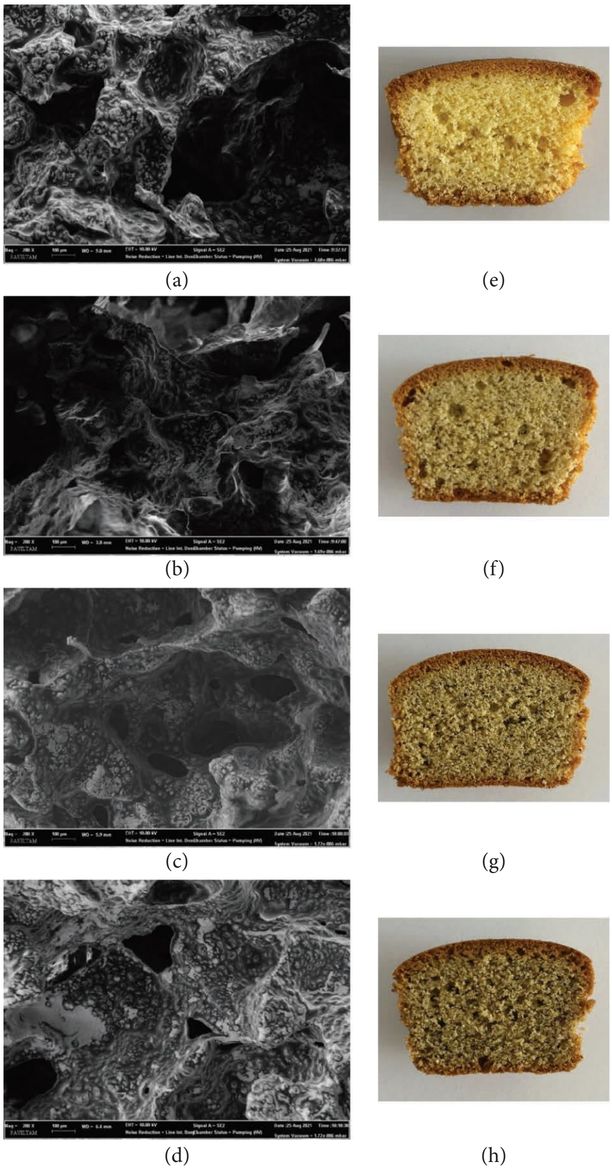

Figure 1: Scanning electron microscopy images (a–d) and photographs (e–h) of muffin samples (magnification 200x). (a) Control SEM image. (b) 15 OSP SEM image. (c) 30 OSP SEM image. (d) 45 OSP SEM image. (e) Control photograph. (f) 15 OSP photograph. (g) 30 OSP photograph. (h) 45 OSP photograph.

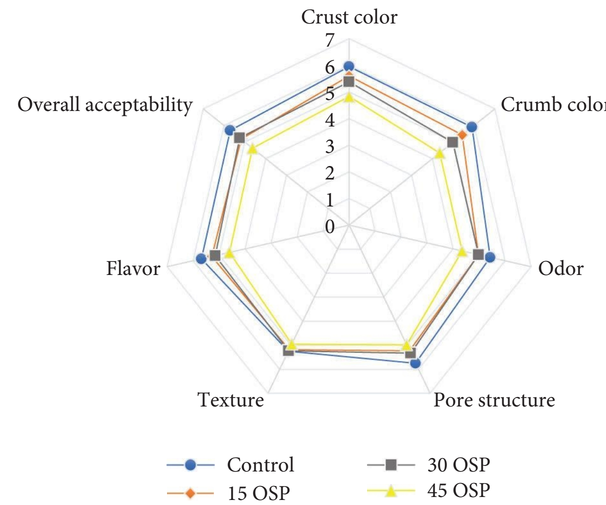

Figure 2: Sensory properties of muffin samples.

Table 8: The weights of criteria obtained from SWARA.

	Criteria	Weights	Ranking
C1	Flavor	0.3037	1
C2	Texture	0.1944	2
C3	Crust color	0.1000	5
C4	Protein	0.1263	3
C5	TDF	0.1167	4
C6	MUFA	0.0682	7
C7	Total EAA	0.0906	6

MUFA: monounsaturated fatty acid; EAA: essential amino acids; TDF: total dietary fiber.

Table 9: The calculation of S_i^*, S_i^-, and C_i^*.

Alternatives	S_i^*	S_i^-	C_i^*	Normalized C_i^*	Ranking
(A1) Control	0.06270	0.03372	0.34968	0.16834	4
(A2) 15 OSP	0.04447	0.02976	0.40091	0.19300	3
(A3) 30 OSP	0.02356	0.04937	0.67696	0.32590	1
(A4) 45 OSP	0.03381	0.06270	0.64965	0.31275	2

the weights of the assessment criteria calculated using this method. In the expert assessment, flavor (30.37%) was identified as the most important criterion, followed by texture (19.44%) and protein (12.63%), respectively, while the least important criterion was monounsaturated fatty acid (6.82%).

The weights of the different criteria obtained from the SWARA were used in the TOPSIS assessment. Table 9 details the distance from the positive ideal solution (S_i^*), the distance from the negative ideal solution (S_i^-), the closeness coefficient (C_i^*), and the normalized closeness coefficient (normalized C_i^*) of each of the muffin samples. According to the normalized C_i^* values, the best alternative formulation was the 30% OSP sample, followed by the 45% OSP sample. While the 45% OSP sample had higher protein, total dietary fiber, monounsaturated fatty acid, and total essential amino acid values than the 30% OSP sample, it was ranked second due to the greater weights assigned to the flavor and texture (sensory properties) criteria than those of the functional properties (protein, total dietary fiber, monounsaturated fatty acid, and total essential amino acid).

4. Conclusions

The only treatment available to those with celiac disease or gluten intolerance is a lifelong gluten-free diet. The gluten-free products available on the market have been found to have poor nutritional value, and so studies into the utilization of ingredients that are rich in various components have been emphasized to support the development of gluten-free food formulations. In the present study, okra seed powder (OSP) was used to enrich gluten-free muffins, leading to increases in phenolic compounds, ash, fat, protein, and dietary fiber with increasing proportions. In addition, a significant increase was noted in the mineral content of the muffins, particularly Mg, P, K, Ca, Fe, and Zn, and the samples supplemented with OSP were found also to be rich in essential amino acids and polyunsaturated fatty acids. Furthermore, the textural hardness, adhesiveness, gumminess, and chewiness values were increased with the supplementation of OSP in increasing quantities. Scanning electron microscopy images showed that the diameter of the air holes in the muffins decreased with increased OSP substitution, while in sensory analysis, the scores of all samples were found to be above the midpoint of the 7-point hedonic scale.

The SWARA-TOPSIS integrated method was used for the determination of the best OSP-added gluten-free muffin formulation, involving an assessment based on seven selected assessment criteria (flavor, texture, crust color, protein, monounsaturated fatty acid, total dietary fiber, and total essential amino acid), the weights of which were calculated using the SWARA method. Alternative gluten-free muffin formulations were then evaluated using the TOPSIS method, revealing the sample with the 30% OSP content to be the most preferred. The findings of the study suggest that OSP has considerable potential for use in gluten-free food formulations. Future studies may assess the bioavailability of bioactive compounds to throw light on the health benefits of enriched gluten-free baked goods.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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