

Article

Spirulina (*Arthrospira platensis*), Chlorella (*Chlorella vulgaris*) and House Cricket (*Acheta domesticus*) as Non-Conventional Sources of Protein for Fortification of Sponge Cake

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Abstract

Enriching bakery products with highly nutritious ingredients, such as microalgae and insect powder, is a promising strategy for developing functional foods. This study aimed to evaluate the effects of spirulina, chlorella, and cricket powder on the quality of sponge cakes. The assessed parameters included color, nutritional value, mineral composition, antioxidant activity, predicted glycemic index (pGI), and sensory properties. The addition of microalgae significantly reduced the L* value and altered the color shade of the sponge cakes, while the insect powder caused milder color changes. The enriched samples contained higher levels of protein (by up to 14%) and minerals, including calcium, magnesium, iron, and zinc. Antioxidant activity was enhanced across all variations, particularly in sponge cakes with insect powder, which showed the highest TPC (47.96 mg GAE), DPPH· (0.107 mM TE), and ABTS·⁺ (0.208 mM TE) levels. Cakes containing spirulina exhibited the highest total flavonoid content (63.95 mg EPI). Additionally, the enriched samples demonstrated a statistically significant reduction in the pGI. Among all the supplemented samples, the sponge cake with cricket powder received the highest consumer acceptance. Overall, enriching sponge cakes with microalgae and cricket powder improved their nutritional value and antioxidant properties, with insect powder offering the best balance between sensory quality and functionality.

Keywords: *Arthrospira platensis*; *Acheta domesticus*; *Chlorella vulgaris*; microalgae; edible insects; functional food



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1. Introduction

Cakes are a large and very popular group of baked goods. Godefroidt et al. [1] distinguish between batter-type and foam-type cakes. The first type is characterized by a high fat content and can be considered an emulsion. The second kind contains small amounts of fat and can be described as foam. A sponge cake is a foam-type cake. Wheat flour, eggs, sugar, and, in some cases, chemical leavening agents are mainly used to make this type of cake.

Despite its popularity, this type of cake is characterized by a high sugar content, which means that eating it increases calorie intake. To mitigate this effect and enhance the nutritional value of these cakes, numerous studies have investigated modifying the sponge cake. These include, among others, gluten-free sponge cake without added sucrose [2], sponge cake with reduced fat content [3], and sponge cake with vegan egg substitutes [4]. The popularity of sponge cake in scientific research may stem from its neutral taste and the

simplicity of its production, which make it a reasonable basis for research. A significant area of study in food, including confectionery, is the development of functional foods. These are characterized by increased biological activity and have positive effects on health, for example, by reducing the risk of chronic diseases [5]. Regarding biscuits as functional foods, such products include cakes supplemented with edible insects [6,7], a mixture of green tea, white tea, and ginger extracts [8], or enriched with olive stone powder [9].

Currently, there is also growing interest in non-conventional sources of protein, such as edible insects (e.g., *Locusta migratoria*, *Tenebrio molitor*, *Bombyx mori*, *Acheta domesticus* [10]) and microalgae (e.g., *Chlorella vulgaris*, *Arthrospira platensis*, *Dunaliella salina*, *Tetraselmis suecica* [11]). The species listed are sources of numerous biologically active compounds. The protein content of *Arthrospira platensis* (spirulina) can reach up to 70% by dry weight [12]. The protein in spirulina is highly digestible and provides all essential amino acids [13]. *Arthrospira platensis* is also a source of vitamins (B, C, D, E), and contains several minerals (e.g., iron, calcium, chromium, phosphorus, magnesium, sodium) [14]. It is also characterized by its content of polyunsaturated fatty acids (PUFAs)—mainly linoleic acid [15], and pigments, including chlorophyll, beta-carotene, c-phycocyanin, and echinenone [14]. Due to its valuable composition, spirulina has antioxidant, anti-inflammatory, and immunomodulatory properties, among others. It also supports the treatment of many diseases, including cardiovascular diseases, lowers blood pressure and glucose levels in diabetic patients, improves metabolic parameters and supports weight loss [16]. Numerous studies have demonstrated the therapeutic potential of spirulina. Regular consumption of spirulina in patients who are overweight and hypertensive improved their BMI (body mass index) and body weight and lowered their blood pressure [17]. It has also been confirmed that spirulina significantly reduces systolic and diastolic blood pressure, serum triglyceride levels, total cholesterol, and low-density lipoprotein cholesterol [18]. Microalgae supplementation as an adjunct to metformin has been shown to provide long-term glycemic control in people with type 2 diabetes [19]. Spirulina also has neuroprotective effects, modulates glial cell activation, and supports the treatment of neurodegenerative diseases (e.g., Alzheimer's disease, Parkinson's disease, and multiple sclerosis) [20]. Spirulina powder is widely used as a food additive. Examples of bakery and confectionery products include bread, breadsticks [21], crostini [22], wheat crackers [23], muffins [24], and biscuits [25]. *Chlorella vulgaris*, similar to spirulina, is regarded as a superfood [26]. This is mainly due to its rich nutritional content. Depending on the growing conditions, the protein content in dry matter ranges from 43% to 58% [27]. This microalgae is also a rich source of unsaturated fatty acids, such as α -linolenic acid, which has a positive effect on the human body by regulating blood lipid levels, reducing the risk of type 2 diabetes, and boosting immunity [28]. Additionally, chlorella is a rich source of various vitamins and minerals. It is rich in B vitamins (folic acid, thiamine, riboflavin, niacin), as well as beta-carotene and tocopherols. It also contains several minerals, including iron, calcium, magnesium, and zinc. *C. vulgaris* is known for its bioactive compounds, which contribute to its role as a natural antioxidant, metabolism regulator, and immunity booster. Bioactive compounds in microalgae can combat oxidative stress and reduce the risk of chronic diseases (e.g., cancer, cardiovascular disease, diabetes). *C. vulgaris* has been proven to strengthen immune functions and contribute to the detoxification of heavy metals from the body. Polysaccharides and carotenoids in microalgae play a role in regulating blood glucose levels and improving insulin sensitivity. Polysaccharides, such as beta-glucans, also modulate the immune response and reduce neuroinflammation. The fibre contained in *C. vulgaris* can reduce fat absorption in the intestines [29]. Chlorella can be used as an additive to foods such as vegan muffins [30], pasta [31], smoothies, protein bars, and various snacks [29]. The house cricket (*Acheta domesticus*), similar to spirulina and chlorella, is characterized by its rich nutritional content. The crude protein content in dry

matter can [32] exceed 76% [28], with digestibility approaching 92% [33]. *Acheta domesticus* contains a range of macro- and micronutrients [34,35]. Comparable to the rising popularity of spirulina, interest in crickets as a non-conventional source of dietary protein and energy has increased markedly in recent years. This may be due to the Commission Implementing Regulation, which allowed the introduction of frozen, dried, and powdered forms of house crickets [36]. Fortifying food with house crickets includes a range of products, including cream soups [37], nut bars [38], muffins [24], and extruded snacks [39]. In addition to providing essential nutrients, insects can support health by containing bioactive molecules such as phytosterols and polyphenolic compounds. Insect proteins serve as precursors to bioactive peptides that exhibit beneficial biological activities, including antihypertensive, antioxidant, anti-inflammatory, and hypocholesterolemic effects [40]. Additionally, studies have shown that consuming insects can reduce reactive oxygen species production in cells and decrease lipid peroxidation. Furthermore, they may increase Nrf2 and glutathione S-transferase levels, proteins that help the body respond to oxidative stress, particularly when glucose levels are elevated [41]. Chitin, often a by-product of insect protein production, is a macromolecular compound with high nutritional and health value. Chitin exhibits several biologically relevant properties, including the ability to reduce serum cholesterol levels, function as a hemostatic agent in tissue repair and exert anticoagulant activity [42].

Current research on non-conventional protein sources primarily concentrates on individual raw materials. Additionally, these studies often focus on specific indicators, such as nutritional or antioxidant properties. This study systematically examines the physico-chemical and bioactive properties of products supplemented with microalgae and insect powder, and compares these two unconventional protein sources. Furthermore, it evaluates consumers' attitudes toward these additive types.

This study aimed to analyze selected characteristics of sponge cake fortified with 5% spirulina (*Arthrospira platensis*), chlorella (*Chlorella vulgaris*), and house cricket (*Acheta domesticus*) powder. The study included an assessment of the products' physical, nutritional, bioactive, and sensory properties. The manuscript presented herein delivers information of considerable value to both prospective consumers and professionals within the confectionery industry.

2. Materials and Methods

2.1. Materials

The ingredients bought at a local supermarket used to make the sponge cake were: wheat flour (type 405) (carbohydrates 71.7%, protein 10%, fat 1%) (GoodMills Polska sp. z o.o., Grodzisk Wielkopolski, Poland), sugar (Pfeifer & Langen Polska S.A., Środa Wielkopolska, Poland), eggs (OVOS sp. z o.o., Biezuń, Poland), spirulina (*Arthrospira platensis*) and chlorella (*Chlorella vulgaris*) powders from organic cultivation (Medicaline Konrad Malitka, Karczew, Poland). From a commercial supplier (CricketsFarm, Lublin, Poland), purchased the crickets *Acheta domesticus* (Fabricius, Orthoptera: Gryllidae) (adult). All chemicals and reagents used were of analytical grade.

2.2. Obtaining Insect Powder

The freeze-dried crickets were used for insect powder preparation (Delta 2–24 LSCplus, Christ, Osterode am Harz, Germany; process parameters: pressure 0.521 mbar, shelf temperature 20 °C, freeze-drying chamber temperature −65 °C, time: 48 h). First, they were ground in a laboratory mill to obtain particles smaller than 850 µm, and then sieved through a 20-mesh sieve to ensure proper particle size control. The powder was sealed in an airtight container and stored in the freezer until needed.

2.3. Sponge Cake Preparation

Sponge cake formulations were developed, incorporating spirulina, chlorella, or house cricket powder as a 5% substitute for wheat flour. The control cake was prepared without the raw materials tested. The recipe included the basic ingredients for a sponge cake: wheat flour (31.18%), sugar (31.18%), and eggs (37.64%). The sponge cake was prepared using the cold method. The egg whites were beaten with sugar until stiff peaks formed and the sugar had completely dissolved. The egg yolks were then added and mixed until smooth. The sifted flour (with non-conventional additives added for the test samples) was added in portions to the egg mixture and gently mixed until combined. The prepared dough was transferred to a baking pan and baked in an oven preheated to 180 °C for 20 min.

2.4. Color Measurements

The instrumental measurement of the color (in the CIE L*a*b* color space) of the obtained sponge cakes was carried out using an EnviSense NH310 colorimeter (3nh, Guangdong Threeneh Technology Co., Ltd., Guangzhou, China). Color differences were determined by: L*—lightness (0—black, 100—white), a* (−a*—green, +a*—red), and b* (−b*—blue, +b*—yellow). Chroma (C*) and hue (h°) were also measured. The total color difference (ΔE) was calculated [43]:

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$$

where ΔL^* , Δa^* , and Δb^* represent differences in the L*, a*, and b* values between the reference sample and the test sample, respectively.

The whiteness index (WI) was calculated [44]:

$$WI = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}}$$

2.5. Nutrient Composition

The content of components such as protein, fat, ash, and moisture was assessed using standard analytical methods [45]. Crude protein content ($N \times 6.25$) was determined by the Kjeldahl method using a Kjeltac 8400 automatic distiller (Foss, Foss Analytical AB, Höganäs, Sweden). Crude fat was analyzed using the Soxhlet extraction method (Tecator Soxtec HT 1043, Gemini, Apeldoorn, Sweden) with hexane as the extraction solvent. The ash content was determined by incinerating the samples and then heating the ash in a muffle furnace at 500 °C (Czylok, Jastrzębie Zdrój, Poland) to constant mass. Moisture content was determined by drying samples at 120 °C in an oven (SUP-65W, Wamed, Warsaw, Poland) until a constant weight was reached. The carbohydrate content was determined using a conversion method based on the formula: 100 – protein content – fat content – ash content – moisture content (in 100 g of fresh sponge cake). The nutritional value was estimated using equation: energy value = 9 kcal × g of fat in 100 g of fresh sponge cake + 4 × g of protein in 100 g of fresh sponge cake + 4 × g of carbohydrates in 100 g of fresh sponge cake [24].

2.6. Mineral Content

For sample mineralization to 0.5 g of each freeze-dried sponge cake sample and powders used, 4 mL of nitric acid (V) was added. The mixtures prepared in this way were mineralized in a microwave oven at 200 °C for 20 min (Mars, Xpress, CEM Corporation, Matthews, NC, USA). The mineralized samples were transferred to 25 mL volumetric flasks and filled to the mark with deionized water. Flame atomic absorption spectrophotometry (FAAS, Solaar 939, Unicam, Ilminster, UK) was used to determine the concentration of mineral ions using an acetylene-air flame (flow rate 2 L/min and 13.5 L/min, respectively). Hollow cathode lamps were used as radiation sources with 766.5 nm for potassium, 589 nm

for sodium, 422.7 nm for calcium, 213.9 nm for zinc, 248.3 nm for iron, and 285.2 nm for magnesium. The operating parameters and instrumental and analytical conditions recommended by the manufacturer were used. Working standard solutions of analytes were prepared from a 1000 mg/L stock solution by successive dilution to the desired concentrations. The calibration graphs for the analytes were linear, with correlation coefficients ranging from 0.9977 to 0.9997 [46].

2.7. Antioxidant Properties

2.7.1. Extraction of Bioactive Compounds

Samples of sponge cake and powders of spirulina, chlorella, and cricket (1 g each) were extracted with 10 mL of a mixture of ethanol and water (4:1, *v/v*). The mixtures were continuously agitated for 120 min using a laboratory shaker. Subsequently, the samples were centrifuged at 3000 g for 10 min. The resulting supernatants were then collected and stored at -18°C until further analysis [47].

2.7.2. ABTS Radical Scavenging Activity

To determine the oxidative potential using the ABTS $\cdot^+$ method, the procedure described by Re et al. [48] was used, with minor changes regarding the amount of ABTS $\cdot^+$ solution. In this method, 2.9 mL of ABTS $\cdot^+$ solution was mixed with 0.1 mL of the tested extract. The samples were allowed to react for 30 min, after which their absorbance was recorded at 734 nm, using deionized water as the blank reference. The scavenging activity was calculated:

$$\text{Scavenging activity (\%)} = \left[1 - \left(\frac{A_{\text{sample}}}{A_{\text{control}}} \right) \right] \times 100$$

where A sample—absorbance of the tested extract and ABTS $\cdot^+$ solution, and A control—absorbance of the ABTS $\cdot^+$ solution.

A six-point calibration curve was constructed using Trolox as a standard. The obtained results were presented as Trolox Equivalent Antioxidant Capacity (TEAC) in mM Trolox.

2.7.3. DPPH Radical Scavenging Activity

The method described by Brand-Williams et al. [49] was used to test antioxidant activity against the DPPH $\cdot$ assay, with minor modifications. In brief, 0.9 mL of a 6 μM DPPH $\cdot$ solution prepared in 75% methanol was mixed with 0.1 mL of the tested extract. After a 30 min reaction period, the absorbance of the samples was measured at 517 nm, using 75% methanol as the blank reference. The scavenging activity was calculated:

$$\text{Scavenging activity (\%)} = \left[1 - \left(\frac{A_{\text{sample}}}{A_{\text{control}}} \right) \right] \times 100$$

where A sample—absorbance of the tested extract and DPPH $\cdot$ solution, and A control—absorbance of the DPPH $\cdot$ solution.

A six-point calibration curve was constructed using Trolox as a standard. The obtained results were presented as Trolox Equivalent Antioxidant Capacity (TEAC) in mM Trolox.

2.7.4. Total Flavonoid Content (TFC)

The method described by Karadeniz et al. [50] was used to evaluate TFC in the tested samples. For this purpose, 5 mL of distilled water and 0.3 mL of a 5% sodium nitrite solution were added to 1 mL of the prepared extract. After vortexing and allowing the mixture to rest for 5 min, 0.6 mL of a 10% aluminum chloride hexahydrate solution was added. Following another 5 min reaction period, 2 mL of 1 M sodium hydroxide was added, and the final volume was adjusted to 10 mL with distilled water. The absorbance was measured at 510 nm,

using the blank sample as a reference. A six-point calibration curve was constructed using epicatechin as a standard. TFC was expressed as milligrams of epicatechin equivalents (EPI) per 100 g of the sample.

2.7.5. Total Phenolic Content (TPC)

The Folin–Ciocalteu spectrophotometric method outlined by Singleton and Rossi [51] was used to determine the TPC in the tested samples. The test extract (0.2 mL) was mixed with 0.2 mL of Folin–Ciocalteu reagent and 3 mL of distilled water. The mixture was thoroughly stirred, and after 3 min, 0.6 mL of a saturated sodium carbonate solution was added, and the mixture was incubated at 40 °C for 30 min. After the specified time had elapsed, the absorbance of the solution was measured at 765 nm against a blank. A six-point calibration curve was constructed using gallic acid monohydrate as a standard. The results obtained were presented as mg of gallic acid equivalent (GAE) per 100 g of sample.

2.8. Predicted Glycemic Index In Vitro

The starch digestibility of the sponge cake samples was assessed in vitro using a modified procedure based on the method described by Monro et al. [52] to determine their predicted glycemic index (GI). The simulated digestion process was conducted in the dark at 37 °C while stirring at 130 rpm. In the first step, 30 mL of water and 0.8 mL of HCl were added to 1 g of the sample, resulting in a pH of 2.5, which was necessary to initiate gastric digestion. This phase began with the addition of 1 mL of a 10% pepsin solution in 0.05 M HCl and lasted for 30 min. For start small intestine phase, 2 mL of 1 M NaHCO₃ and 5 mL of a 0.1 M phosphate buffer (pH 6) were added, followed by 4.6 mg of amyloglucosidase and 5 mL of 2.5% pancreatin in 0.1 M phosphate buffer (pH 6). The total volume of hydrolysates was adjusted to 55 mL using distilled water. At intervals of 0, 20, 30, 60, 90, 120, and 180 min after the start of amylolysis, 1.0 mL aliquots of digesta were transferred to 4 mL of absolute ethanol to inactivate the enzymes [53]. The glucose content of the samples (mg glucose/g sample) was determined using the GOPOD (Glucose Oxidase Peroxidase) method. The assay kit employs high-purity glucose oxidase and peroxidase. To prepare reagent solutions, the contents of a bottle of GOPOD reagent enzymes (glucose oxidase plus peroxidase and 4-aminoantipyrine, freeze-dried powder) were dissolved in GOPOD reagent buffer (pH 7.4). Next, 10 µL of the sample was mixed with 300 µL of the reagent solution and incubated at 40 °C for 20 min. The absorbances of samples and the D-glucose standard were measured at 510 nm against the reagent blank. The concentration of glucose was calculated as the ratio of the sample's absorbance to the standard's absorbance. The glucose content was then plotted as a function of time, and the areas under the hydrolysis curves (AUCs) were calculated. The hydrolysis index (HI) was calculated as the ratio of the sample's AUC to that of the reference food, white bread. Finally, the predicted glycemic index was calculated using the formula established by Goñi, Garcia-Alonso, and Saura-Calixto [54]:

$$\text{GI (\%)} = 39.71 + 0.549 \times \text{HI}$$

2.9. Consumer Acceptance Evaluation

The sponge cake was divided into equal portions, each assigned a unique three-digit code. The organoleptic evaluation was conducted with 42 participants (29 women and 13 men) aged 19–36 years. The participants in the evaluation were students and employees of the University of Life Sciences in Lublin. A 9-point scale was used to measure preferences, where the ratings meant: 1—“dislike extremely”; 5—“neither like nor dislike”; 9—“like extremely” [55]. Another evaluation method was ranking. Consumers were asked to rank the samples from best (1st place) to worst (3rd place). The sample in 1st place was awarded 3 points, the sample in 2nd place was awarded 2 points, and the sample in 3rd place was

awarded 1 point [24]. Plain water was used to rinse the mouth before and after sample collection.

2.10. Statistical Analysis

All assays presented in the experiment were replicated at least three times. Results are presented as means along with standard deviation. Statistical analysis was performed using Statistica 13.3 (StatSoft, Krakow, Poland) and Excel 2019 (Microsoft, Washington, DC, USA). A one-way analysis of variance (ANOVA) was used to compare group means. Prior to the analysis, the assumptions of normality and homogeneity of variances were assessed using the Shapiro–Wilk test and Levene’s test, respectively. Since the assumption of equal variances was satisfied ($p > 0.05$), the standard ANOVA procedure was utilized. Post hoc comparisons were performed using Tukey’s HSD test. All statistical hypotheses were verified at a significance level of $p < 0.05$.

3. Results and Discussion

3.1. Color Measurements

Color is one of the most important quality characteristics of food. It provides information about its freshness and, at the same time, strongly influences the product’s sensory appeal as perceived by consumers [56]. The addition of the tested raw materials affects the color parameters of the sponge cakes obtained, and the measurement results are presented in Table 1. The L^* parameter, which determines lightness, was highest for the control sample (71.90 ± 1.24) and did not differ significantly from that of the cake with cricket (70.79 ± 2.21). In samples containing microalgae, a significant decrease in the L^* parameter was observed (53.45 ± 1.43 for the cake with chlorella and 42.31 ± 1.07 for the cake with spirulina). Cakes with spirulina and chlorella had significantly lower a^* values (-0.89 ± 0.21 and -1.13 ± 0.47 , respectively) than the control sample (1.75 ± 0.19), indicating a shift toward a greener shade. In the case of a cake with the addition of the edible insect, the a^* parameter was significantly higher (2.72 ± 0.28) compared to the control cake, so the addition caused a change in color to a more red hue. For the b^* parameter, the highest value was observed in the cake containing chlorella (20.67 ± 1.30). The cake with this addition exhibited the highest yellow color. The sample with spirulina also had an increased b^* value (19.34 ± 1.23), but to a lesser extent than the cake with chlorella, and did not differ significantly from the control. The addition of crickets caused the color to shift to a bluer hue (17.24 ± 0.78) compared to the control cake. The sponge cake fortified with house crickets had a lower color saturation C^* (17.46 ± 0.77) compared to the sponge cake enriched with spirulina (19.45 ± 1.27) and chlorella (20.20 ± 1.48). Changes were also observed in the hue h° , with the highest value for cakes enriched with microalgae (92.13 ± 1.20 for the spirulina variant and 93.09 ± 2.10 for the chlorella variant) and the lowest for the sponge cake with edible insects (81.03 ± 0.98). The non-conventional additives used increased the total color difference (ΔE). The total color difference was 29.72 for the sponge cake with spirulina, 18.76 for the cake enriched with chlorella, and 2.19 for the cake with insect powder. The general appearance of the prepared sponge cakes is shown in Figure 1.

The color change in baked goods (e.g., bread, muffins, or sponge cakes) depends on many factors. The main ones include baking temperature and time, chemical composition, and the color of the raw ingredients [57]. The non-conventional additives used in the study are darker in color than wheat flour, so the color change in the enriched sponge cake is natural. The main factor influencing the color of the cake with spirulina was C-phycocyanin, a water-soluble, non-toxic, and intensely blue-green photosynthetic pigment [58]. This ingredient has many benefits for the human body, including antioxidant activity, anti-cancer activity, and immune regulation [59]. In baked goods containing chlorella, the color changed

due to the presence of chlorophyll in the algae and, to a lesser extent, carotenoids. Similar to c-phycoyanin, chlorella and its derivatives have therapeutic applications, including anti-inflammatory and wound-healing properties, antioxidant and radioprotective effects [60]. The primary pigment present in house crickets is melanin [61]. An additional factor that may have affected the color of the finished sponge cake was the intensification of the Maillard reaction during baking, driven by increased protein content [43]. The results of the study are consistent with those obtained in other research. Adding spirulina to vegan cakes resulted in a significant decrease in the L^* parameter for the cake's crumb and crust [62]. In bread, the addition of spirulina resulted in significant darkening of the products, decreases in the a^* and b^* parameters, and a high total color difference [63]. Color measurements of vegan muffins enriched with chlorella showed decreases in L^* and a^* , and an increase in h° , giving them a characteristic green color [30]. The addition of cricket mealworm, and buffalo worm, powders to sponge cakes decreased the L^* , a^* , and b^* parameters and increased the total color difference [7]. Significantly lower values of brightness (L^*) and yellowness compared to the control, and no significant difference in the a^* parameter, were observed in bread with the addition of powder from house crickets [64].

Table 1. Color determinants of sponge cake.

Sample	L^*	a^*	b^*	C^*	h°	ΔE	WI
CON	71.90 ± 1.24^a	1.75 ± 0.19^b	18.87 ± 0.84^{bc}	18.95 ± 0.86^{ab}	84.55 ± 0.35^b	-	66.11
CS	42.31 ± 1.07^c	-0.89 ± 0.21^c	19.34 ± 1.23^{ab}	19.45 ± 1.27^a	92.13 ± 1.20^a	29.72	39.14
CCH	53.45 ± 1.43^b	-1.13 ± 0.47^c	20.67 ± 1.30^a	20.20 ± 1.48^a	93.09 ± 2.10^a	18.76	49.06
CC	70.79 ± 2.21^a	2.72 ± 0.28^a	17.24 ± 0.78^c	17.46 ± 0.77^b	81.03 ± 0.98^c	2.19	65.97

Lightness (L^*) and color (a^* —redness, b^* —yellowness). Chroma (C^*) and hue (h°). ΔE —total color difference. WI—whiteness index. CON—control sample; CS—sponge cake with spirulina; CCH—sponge cake with chlorella; CC—sponge cake with cricket. In each column, values marked with the same letters do not differ significantly at $p < 0.05$ (Tukey's post hoc test).

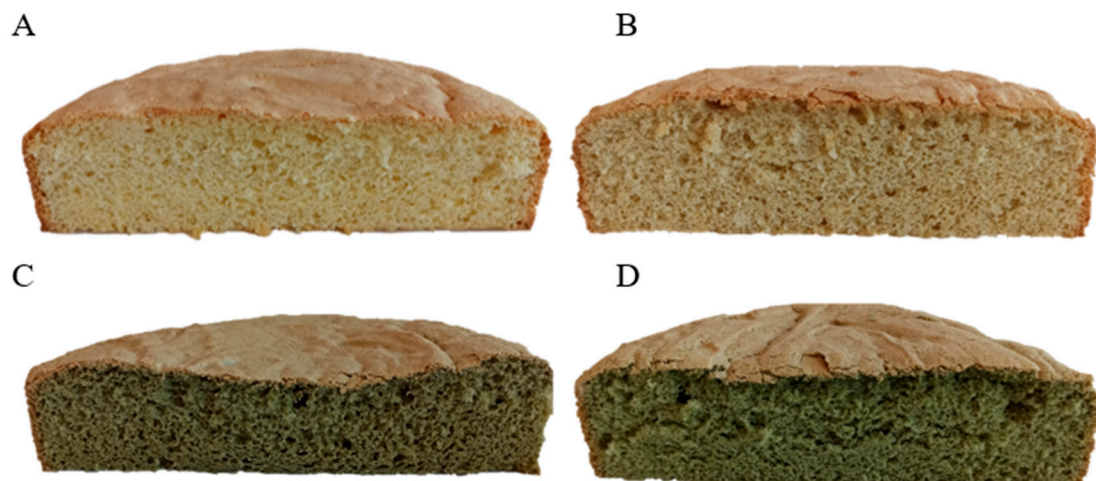


Figure 1. Appearance of the obtained sponge cake; (A)—control sample; (B)—sponge cake with cricket; (C)—sponge cake with spirulina; (D)—sponge cake with chlorella.

3.2. Nutrient Composition

The nutritional values of the tested sponge cake samples and the fortification powders are shown in Table 2. It is well known that microalgae, including spirulina and chlorella, and edible insects are valuable sources of protein, as confirmed by the study presented. The protein content of the powder from spirulina was 70.20 ± 0.23 g/100 g FM, from chlorella

was 59.18 ± 0.37 g/100 g FM, and from cricket powder was 73.24 ± 0.17 g/100 g FM. Consequently, enhancing the sponge cake with spirulina, chlorella, and edible insect powder led to a notable increase in the protein content of the produced product, recorded at 9.78 ± 0.10 /100 g FM, 9.26 ± 0.07 /100 g FM, and 9.73 ± 0.03 /100 g FM, respectively. Thus, the lowest protein content (8.55 ± 0.03 /100 g FM) was recorded in the control sponge cake. Cricket powder contained approximately twice as much fat content (12.01 ± 0.04 g/100 g FM) compared to microalgae (spirulina 5.60 ± 0.01 g/100 g FM and chlorella 6.14 ± 0.17 g/100 g FM). Thus, the sponge cake enriched with cricket powder contained the highest fat content (3.26 ± 0.02 g/100 g FM), followed by those enriched with spirulina (3.13 ± 0.10 g/100 g FM) and chlorella (3.12 ± 0.02 g/100 g FM). The low carbohydrate content in cricket powder (0.8 ± 0.08 g/100 g FM) meant that the sponge cake enriched with this additive had the lowest carbohydrate content (59.58 ± 0.07 g/100 g FM) compared to the control products (62.05 ± 0.09 g/100 g FM) or containing spirulina (61.41 ± 0.06 g/100 g FM) and chlorella (61.27 ± 0.05 g/100 g FM) powders. Among the additives used, chlorella powder had the highest ash content (9.35 ± 0.09 g/100 g FM), followed by spirulina (6.21 ± 0.03 g/100 g FM) and cricket powder (4.43 ± 0.03 g/100 g FM). Hence, the sponge cake enriched with chlorella and spirulina had the highest ash content (0.77 ± 0.01 g/100 g FM and 0.77 ± 0.01 g/100 g FM, respectively) among the enriched products. The sponge cake containing cricket powder had a higher ash content (0.72 ± 0.01 g/100 g FM) than the control cake (0.68 ± 0.01 g/100 g FM). The water content in the sponge cakes ranged from 24.91 ± 0.21 g/100 g FM (variant with spirulina) to 26.71 ± 0.59 g/100 g FM (variant with crickets). The energy value of the sponge cakes obtained ranged from 306.58 kcal/100 g (cake enriched with cricket powder) to 312.93 kcal/100 g (cake enriched with spirulina powder).

Table 2. Nutritional value of muffins and powders used.

Sample	Protein	Fat	Carbohydrates	Ash	Moisture	Energy Value
	g/100 g FM					kcal/100 g
CON	8.55 ± 0.03 ^c	3.05 ± 0.04 ^b	62.05 ± 0.09 ^a	0.68 ± 0.01 ^c	25.72 ± 0.82 ^{ab}	309.85
CS	9.78 ± 0.10 ^a	3.13 ± 0.10 ^{ab}	61.41 ± 0.06 ^b	0.77 ± 0.01 ^a	24.91 ± 0.21 ^b	312.93
CCH	9.26 ± 0.07 ^b	3.12 ± 0.02 ^{ab}	61.27 ± 0.05 ^b	0.77 ± 0.01 ^a	25.58 ± 0.62 ^{ab}	310.02
CC	9.73 ± 0.03 ^a	3.26 ± 0.02 ^a	59.58 ± 0.07 ^c	0.72 ± 0.01 ^b	26.71 ± 0.59 ^a	306.58
spirulina powder	70.20 ± 0.23	5.60 ± 0.01	11.93 ± 0.12	6.21 ± 0.03	6.06 ± 0.29	378.92
chlorella powder	59.18 ± 0.37	6.14 ± 0.17	20.07 ± 0.04	9.35 ± 0.09	5.26 ± 0.10	372.26
cricket powder	73.24 ± 0.17	12.01 ± 0.04	0.8 ± 0.08	4.43 ± 0.03	9.52 ± 0.18	404.25

CON—control sample; CS—sponge cake with spirulina; CCH—sponge cake with chlorella; CC—sponge cake with cricket. In each column, values marked with the same letters do not differ significantly at $p < 0.05$ (Tukey's post hoc test).

Microalgae and edible insects, particularly valued for their high protein content, appear to be suitable for food fortification. Spirulina contains significantly higher protein levels (55–70%) than commonly consumed foods. In addition, it contains all essential amino acids, including lysine, leucine, histidine, phenylalanine, methionine, threonine, tryptophan, and valine. However, it should be emphasized that their numbers depend on the conditions in which microalgae are cultivated [16]. Chlorella is also important nutritionally, as it contains high levels of protein (up to about 60%) and, in autotrophic or heterotrophic media, has the ability to synthesize essential and nonessential amino acids [27]. The protein content of edible insects varies widely, ranging from 13 to 80%, and depends on many factors, including the feed mixtures used and the varying water content

or stages of metamorphosis. It is also worth noting the high content of unsaturated fatty acids and low carbohydrate content (mainly chitin) [40]. The data obtained in the study also confirm the high nutritional value of spirulina and chlorella microalgae, as well as edible insects, such as the house cricket. The high protein content of the tested powders led to an increase in this component in fortified products. This is extremely important, as it is already estimated that approximately 1 in 9 people worldwide are undernourished, and the most significant factor is protein-energy malnutrition, i.e., a lack of adequate calorie and protein intake [65]. As a result, food futurologists predict significant changes in the type of food consumed in the coming years [66], creating a huge opportunity for microalgae and edible insects, among other things, given their high nutritional value. In addition, the growing demand for functional foods is already prompting food manufacturers to make changes and innovations, including in confectionery products. Therefore, the data obtained in this study are valuable not only for potential consumers but also for the food industry seeking innovative, high-nutritional-value products.

3.3. Mineral Content

The mineral content of the sponge cakes and the powders used to fortify them is shown in Table 3. The additives used for enrichment, such as spirulina, chlorella, and house crickets, are rich in calcium (99.33 ± 1.29 mg/100 g FM, 108.19 ± 5.22 mg/100 g FM and 87.18 ± 0.37 mg/100 g FM, respectively) which meant that the sponge cake enriched with them had a significantly higher calcium content compared to the control (20.24 ± 1.15 mg/100 g FM). The calcium content in enriched sponge cakes ranged from 26.50 ± 0.08 mg/100 g FM (spirulina-enriched cake) to 28.05 ± 0.37 mg/100 g FM (cricket-enriched cake) and did not differ significantly between them. Due to the fact that chlorella powder had a high magnesium content (564.70 ± 7.46 mg/100 g FM), the cake enriched with this additive had the highest content of this element (20.49 ± 0.08 mg/100 g FM)—almost twice as high as in the control (10.45 ± 0.25 mg/100 g FM). The spirulina powder used for enrichment had a higher magnesium content (245.42 ± 1.55 mg/100 g FM) compared to cricket powder (114.80 ± 0.78 mg/100 g FM), thus the product enriched with *Arthrospira platensis* had a significantly higher magnesium content (15.18 ± 0.28 mg/100 g FM) compared to the cake with edible insect additive (11.33 ± 0.22 mg/100 g FM). The additives used for enrichment are rich in potassium, with the highest content found in powdered spirulina (1448.41 ± 1.21 mg/100 g FM), followed by insect powder (1296.22 ± 3.03 mg/100 g FM) and chlorella (1084.55 ± 3.73 mg/100 g FM). Therefore, fortified sponge cakes contained higher potassium content (with the addition of cricket powder 127.03 ± 1.10 mg/100 g FM, with the addition of spirulina 122.19 ± 1.94 mg/100 g FM, and with the addition of chlorella 112.25 ± 0.82 mg/100 g FM) compared to the control cake (96.54 ± 0.55 mg/100 g FM). Similar correlations were observed for sodium, with the highest content found in powdered spirulina (606.93 ± 0.28 mg/100 g FM), followed by insect powder (408.26 ± 2.99 mg/100 g FM) and chlorella (138.27 ± 6.72 mg/100 g FM). Thus, cakes enriched with spirulina and cricket powder had significantly higher sodium content, 166.03 ± 0.42 mg/100 g FM and 163.39 ± 1.84 mg/100 g FM, respectively. The cake containing chlorella had a significantly higher sodium content (151.21 ± 0.55 mg/100 g FM) than the control cake (140.74 ± 0.55 mg/100 g FM). Microalgae, including spirulina and chlorella, were characterized by high iron content (35.59 ± 0.20 mg/100 g FM and 34.65 ± 0.11 mg/100 g FM, respectively), which resulted in a significant increase in this element in cakes enriched with them. Among the tested baked goods, the highest iron content was found in the spirulina sample (1.85 ± 0.06 mg/100 g FM), followed by the chlorella sample (1.66 ± 0.01 mg/100 g FM). The cake enriched with insect powder had a significantly higher iron content (1.28 ± 0.03 mg/100 g FM) compared to the control

cake (1.17 ± 0.01 mg/100 g FM). Regarding zinc, only sponge cake with added cricket powder had a significantly higher content of this element (1.70 ± 0.06 mg/100 g FM), which was related to the high zinc content in the cricket powder used for enrichment (22.65 ± 0.65 mg/100 g FM).

Table 3. Mineral content of sponge cake and powders used.

Sample	Ca	Mg	K	Na	Fe	Zn
	mg/100 g FM					
CON	20.24 ± 1.15^b	10.45 ± 0.25^c	96.54 ± 0.55^c	140.74 ± 0.55^c	1.17 ± 0.01^d	0.88 ± 0.01^b
CS	26.50 ± 0.08^a	15.18 ± 0.28^b	122.19 ± 1.94^a	166.03 ± 0.42^a	1.85 ± 0.06^a	0.92 ± 0.03^b
CCH	27.20 ± 0.52^a	20.49 ± 0.08^a	112.25 ± 0.82^b	151.21 ± 0.55^b	1.66 ± 0.01^b	1.18 ± 0.09^b
CC	28.05 ± 0.37^a	11.33 ± 0.22^c	127.03 ± 1.10^a	163.39 ± 1.84^a	1.28 ± 0.03^c	1.70 ± 0.06^a
spirulina powder	99.33 ± 1.29	245.42 ± 1.55	1448.41 ± 1.21	606.93 ± 0.28	35.59 ± 0.20	1.62 ± 0.06
chlorella powder	108.19 ± 5.22	564.70 ± 7.46	1084.55 ± 3.73	138.27 ± 6.72	34.65 ± 0.11	2.37 ± 0.11
cricket powder	87.18 ± 0.37	114.80 ± 0.78	1296.22 ± 3.03	408.26 ± 2.99	4.42 ± 0.07	22.65 ± 0.65

CON—control sample; CS—sponge cake with spirulina; CCH—sponge cake with chlorella; CC—sponge cake with cricket. In each column, values marked with the same letters do not differ significantly at $p < 0.05$ (Tukey's post hoc test).

The study demonstrated that spirulina and chlorella microalgae, as well as house crickets, are valuable sources of minerals. Replacing even a small portion of flour (5%) with the tested additives resulted in a product with an increased content of selected minerals. Of particular importance is the significant increase in iron content in microalgae samples (from 41.88% to 58.12%) compared to unenriched sponge cake. This is particularly important because the consequences of iron deficiency are serious, including weakened immune function, impaired cognitive function, and the risk of impaired neurological development [67]. The products obtained in the present study are particularly important for vegetarians, as they provide a significant increase in iron and calcium content (from 30.93% to 38.59%). They are at risk of deficiency in this element. Spirulina contains calcium and phosphorus in amounts comparable to those in milk, with high bioavailability and proper calcium-to-phosphorus ratio. This eliminates the risk of decalcification, which can occur with increased phosphorus content in food [16]. Importantly, the sponge cake enriched with microalgae had a significantly higher magnesium content (from 45.26% to 96.08%) compared to the unenriched variant. Magnesium is a key cofactor in hundreds of enzymatic reactions that regulate a range of functions, e.g., neuromuscular function, energy metabolism, cardiovascular health, immune defense, bone integrity, and mental well-being. Despite its physiological relevance, magnesium deficiency persists as a prevalent condition within the population, with main causes including insufficient dietary intake, lifestyle factors, chronic diseases, and medication use [68]. Notably, the study found an approximately 93% increase in zinc content in sponge cake enriched with cricket powder compared to the unenriched variant. Zinc is a micronutrient that plays a critical role in human physiology, as it is required for the activity of all major classes of enzymes. Nevertheless, inadequate zinc intake remains a widespread global concern, particularly in low- and middle-income countries [69]. Therefore, enriching popular food products with powdered raw materials rich in this element seems to be a good solution to the problem of zinc deficiency.

3.4. Antioxidant Properties

In addition to achieving the sensory characteristics desired by consumers, increasing the biological activity of foods is also a critical aspect of designing new foods. To assess antioxidant properties, a study measured total phenolic content (TPC) and total flavonoid content

(TFC). Spectrophotometric methods were used to measure antioxidant activity against DPPH· and ABTS. The test results are presented in Table 4. Among the powders tested, the highest polyphenol content was found in house cricket powder (566.11 ± 8.87 mg GAE/100 g), followed by spirulina powder (315.75 ± 5.04 mg GAE/100 g) and chlorella powder (249.25 ± 4.21 mg GAE/100 g). The antioxidant activity of the tested powders was similar. The highest activity against both DPPH· and ABTS was exhibited by insect powder (0.784 ± 0.01 mM TE/100 g and 0.806 ± 0.03 mM TE/100 g, respectively), followed by spirulina powder (0.341 ± 0.02 mM TE/100 g and 0.725 ± 0.03 mM TE/100 g, respectively) and chlorella powder (0.275 ± 0.02 mM TE/100 g and 0.487 ± 0.01 mM TE/100 g, respectively). Regarding the total flavonoid content, the highest amounts were found in microalgae powders (spirulina 435.17 ± 4.25 mg EPI/100 g, chlorella 368.37 ± 3.14 mg EPI/100 g), while insect powder had a lower content of these compounds (167.1 ± 2.11 mg EPI/100 g). As with the raw materials used for fortification, the total phenolic content varied significantly between the sponge cake samples tested. The highest polyphenol content was observed in sample CC, with a TPC of 47.96 ± 1.40 mg GAE/100 g. This value was significantly higher ($p < 0.05$) than that of all other samples. The second-highest polyphenol content was observed in sample CS, with a TPC of 37.62 ± 1.63 mg GAE/100 g. Although this value was significantly lower than that of the CC sample, it was noticeably higher than that of the CCH and CON samples. The lowest polyphenol content was observed in the control sample (CON), with a TPC of 23.02 ± 0.62 mg GAE/100 g. This result was significantly lower than that of the other variants ($p < 0.05$), confirming that the additives used to enrich the sponge cake positively affected the TPC.

Table 4. Total polyphenol and flavonoid content and antioxidant properties of sponge cake.

Sample	TPC (mg GAE/100 g)	TFC (mg EPI/100 g)	DPPH· (mM TE/100 g)	ABTS·+ (mM TE/100 g)
CON	23.02 ± 0.62^d	30.67 ± 0.20^c	0.017 ± 0.001^d	0.088 ± 0.002^d
CS	37.62 ± 1.63^b	63.95 ± 4.07^a	0.031 ± 0.002^b	0.167 ± 0.001^b
CCH	30.87 ± 0.2^c	50.85 ± 3.07^b	0.024 ± 0.003^c	0.115 ± 0.003^c
CC	47.96 ± 1.4^a	33.37 ± 0.43^c	0.107 ± 0.003^a	0.208 ± 0.002^a
spirulina powder	315.75 ± 5.04	435.17 ± 4.25	0.341 ± 0.02	0.725 ± 0.03
chlorella powder	249.25 ± 4.21	368.37 ± 3.14	0.275 ± 0.02	0.487 ± 0.01
cricket powder	566.11 ± 8.87	167.1 ± 2.11	0.784 ± 0.01	0.806 ± 0.03

CON—control sample; CS—sponge cake with spirulina; CCH—sponge cake with chlorella; CC—sponge cake with cricket. In each column, values marked with the same letters do not differ significantly at $p < 0.05$ (Tukey's post hoc test).

The measured flavonoid content (TFC), expressed as milligrams of epicatechin equivalent per 100 g, showed statistically significant differences among the analyzed samples of sponge cake. The highest flavonoid content was observed in the CS samples, with a TFC of 63.95 ± 4.07 mg EPI/100 g. Following this, the CCH sample exhibited a TFC of 50.85 ± 3.07 mg EPI/100 g. The difference between the CS and CCH samples was statistically significant, while the flavonoid content in the CCH sample was noticeably higher than that in the CC and CON samples. The CON and CC samples had comparably low flavonoid contents, measuring 30.67 ± 0.20 mg EPI/100 g and 33.37 ± 0.43 mg EPI/100 g, respectively, with no significant difference between them.

In contrast to the polyphenol content, which was highest in the sample supplemented with cricket powder, the highest level of flavonoids was found in the sample supplemented with spirulina. This indicates that the sample with spirulina powder contains more flavonoids than total polyphenols, whereas the sample with cricket powder has the highest total phenolic content (TPC) but a relatively low total flavonoid content (TFC). The flavonoid content does not always show a direct linear relationship with the total polyphenol content.

This is because polyphenols also encompass phenolic acids, tannins, stilbenes, and other classes of compounds. In certain matrices, flavonoids represent only a fraction of the total polyphenols [70]. As a result, samples with a high TPC may exhibit a moderate TFC if other classes of phenolic compounds are more prevalent. The difference also depends on the type of raw material used. When examining plant-based materials such as spirulina and chlorella, we observe a correlation between total phenolic and total flavonoid contents. In contrast, insects serve as a different type of raw material, and the composition of their bioactive compounds varies significantly from that of plants [42].

All sponge cakes with non-conventional additives showed significantly higher antioxidant activity against DPPH· and ABTS than the cake without additives. The highest antioxidant activity values were found in sponge cake with added cricket (0.107 ± 0.003 mM TE/100 g and 0.208 ± 0.002 mM TE/100 g for DPPH· and ABTS, respectively). The fortified cake with the lowest antioxidant activity was the sponge cake with chlorella (0.024 ± 0.003 mM TE/100 g for DPPH· and 0.115 ± 0.003 mM TE/100 g for ABTS). The sponge cake with spirulina powder added showed antioxidant activity of 0.031 ± 0.002 mM TE/100 g against DPPH· and 0.167 ± 0.001 mM TE/100 g using the ABTS method.

Several studies support the notion that incorporating non-conventional protein sources enhances the antioxidant activity and phenolic compound content in fortified foods. For instance, sponge cakes enriched with buffalo worm, cricket, and mealworm powder demonstrated significantly higher antioxidant activity against DPPH· and ABTS [7]. Specifically, when house cricket flour was added, the DPPH· activity increased from 4.95 mg Tx/g in the standard cake to 13.2 mg Tx/g in the cake with a 30% cricket flour addition. Similarly, the ABTS activity rose from 5.98 mg Tx/g for the control cake to 15.93 mg Tx/g for the cake with a 30% addition.

Additionally, including crickets in rice crackers elevated their antioxidant activity against both DPPH· and ABTS, along with an increase in total phenolic content [71]. The incorporation of microalgae, such as chlorella and spirulina, has likewise been shown to enhance the antioxidant activity of foods. For example, adding chlorella to brioche increased DPPH· inhibition by over 47%, changing from 0.80 to 1.18 μ mol AAE/g DW (dry weight) [72]. In another instance, incorporating spirulina into a whey-based sports drink resulted in a more than 24% increase in antioxidant activity, rising from 57.20 to 71.05 mg/mL in the sample with the highest 3% addition. Furthermore, the phenolic compound content in this drink increased by 15%, from 60.75 to 70.05 mg GAE/100 g [73].

3.5. Predicted Glycemic Index In Vitro

The in vitro hydrolysis index of starch (HI) and the predicted glycemic index values (pGI) of sponge cakes are presented in Figure 2. Incorporating spirulina (CS), chlorella (CCH), and cricket powder (CC) into the formulations led to significant alterations in both pGI and HI compared with the control sample (CON) ($p < 0.05$). The sponge cake without any added ingredients exhibited the highest pGI value (53.58), which is consistent with conventional baked products that contain large amounts of rapidly digestible carbohydrates and minimal protein and fiber. The greatest decrease in pGI was noted in the sponge cake enriched with spirulina. This effect is likely attributable to its elevated protein content and the presence of bioactive pigments, including phycocyanin and chlorophyll, which may modulate digestive enzyme activity [74]. The inclusion of cricket powder (CC) also lowered the pGI to a similar level of 52.78. In comparison, chlorella resulted in a lesser reduction in pGI, bringing it down to 53.12, possibly due to its lower protein content.

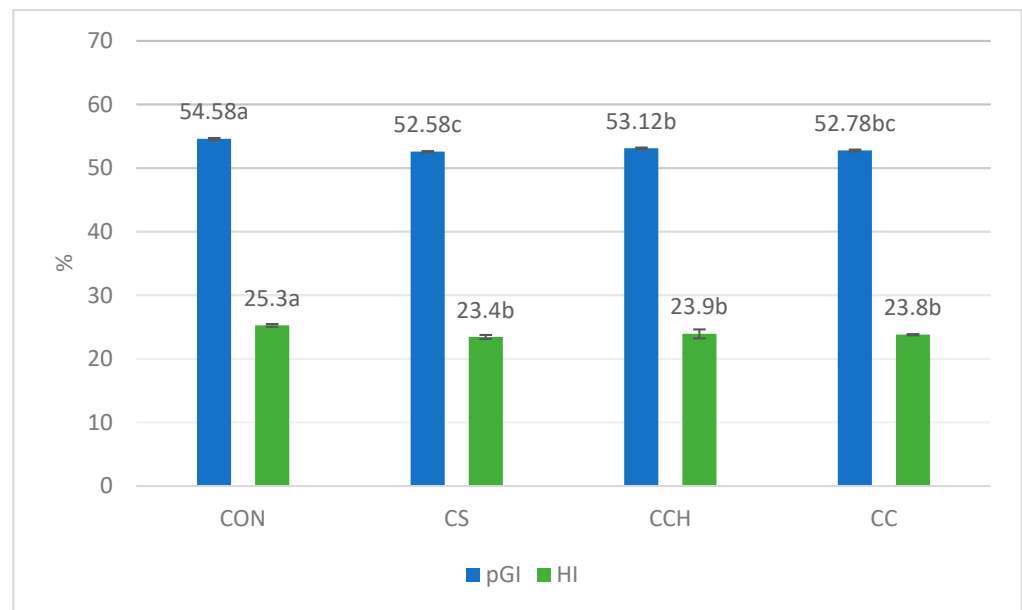


Figure 2. The in vitro starch hydrolysis index and in vitro predicted glycemic index values of muffins. HI—hydrolysis index of starch; pGI—predicted glycemic index values; CON—control sample; CS—sponge cake with spirulina; CCH—sponge cake with chlorella; CC—sponge cake with cricket. Data values of each parameter with different lowercase letters are significantly different ($p < 0.05$).

The HI value for the control sample (CON) was 25.3, which was significantly higher than in all fortified variants. This result reflects a more intense rate of carbohydrate hydrolysis, characteristic of conventional sponge cake formulations. In contrast, all enriched sponge cakes exhibited markedly reduced HI values compared with the control, with no significant differences among the fortified samples.

The findings of this study demonstrate that incorporating spirulina, chlorella, and cricket powder into sponge cake formulations significantly reduced both pGI and HI values compared with the control sample. The underlying mechanisms associated with this effect align with previously reported observations in the literature. As indicated Chao et al. [75], various factors can influence the reduction in the glycemic index of starchy products, including the presence of other food components. Electrostatic and hydrophobic interactions occurring between starch and both lipids and proteins enhance the structural organization of starch granules, which in turn slows down their enzymatic degradation. In the samples analyzed, the protein-based additives (spirulina, chlorella, and cricket powder) likely contributed to the formation of such complexes, thereby restricting the accessibility of starch to amylolytic enzymes.

Additionally, as highlighted by Barrett et al. [76], phenolic compounds can inhibit digestive enzyme activity, thereby delaying glucose absorption and lowering postprandial glycemia. The additives used, such as microalgae and insects, are rich in polyphenols, which may have further contributed to the observed reduction in the predicted glycemic index of our samples. [77]. The reduction in the hydrolysis index observed in all variants with additives supports the idea that such structures may have formed within the biscuit matrix.

From a functional foods perspective, these results are significant, especially given the increasing consumer demand for low-glycemic index foods. The additives used—spirulina, chlorella, and cricket powder—not only enhance nutritional value by increasing protein and bioactive ingredient levels but also support glycemic control. Similar findings were reported by Batista et al. [23] regarding microalgae and by Zielińska et al. [24,43] concerning insects. These results suggest that unconventional protein sources can serve a dual purpose: enriching food with essential nutrients and improving its health-promoting properties.

3.6. Consumer Acceptance Evaluation

The results of consumer acceptance of the sponge cake, as measured using a nine-point hedonic scale and ranking method, are presented in Table 5. Overall, the prepared sponge cake variants were generally acceptable to consumers, with the control sponge cake receiving the highest rating. It also received the highest number of points (146) in the ranking method. The control sponge cake received the highest score for color (8.38 ± 0.85), possibly because consumers are accustomed to the classic color of this popular confectionery product. The additives used significantly altered the sponge cake's color, resulting in lower color ratings for the variants with spirulina (6.19 ± 1.63), chlorella (6.83 ± 1.90), and crickets (6.79 ± 1.63). In terms of smell, only the sponge cake with chlorella received a significantly lower score (5.43 ± 2.20), while the other variants were rated equally highly (from 6.83 ± 1.71 to 7.60 ± 1.29). The texture of the enriched sponge cakes was rated lower by consumers (from 6.55 ± 1.68 to 7.10 ± 1.43) than that of the control (7.90 ± 1.08). In terms of taste, the lowest score was given to the chlorella-enriched sponge cake (6.12 ± 2.13), but this rating was still positive, indicating "I like it quite a bit." The sponge cake with spirulina was rated as "moderately liked" (7.12 ± 1.61) in terms of taste, while in terms of this quality indicator, the variant with crickets received the highest score among the enriched cakes (7.69 ± 1.20). Similarly, in the overall assessment of products, among sponge cakes enriched with unconventional additives, the variant with crickets received the highest score (7.24 ± 1.16), whereas the variant with chlorella received the lowest (6.21 ± 1.91). A similar correlation was observed in the ranking method, with a high score (110 points, 2nd place) for the sponge cake with edible insects and the lowest score (69 points, 4th place) for the cake with chlorella.

Table 5. Consumer acceptance analysis and results of preference ranking of sponge cake.

Sample	Color	Smell	Texture	Taste	Overall Impression	Ranking
CON	8.38 ± 0.85^a	7.60 ± 1.29^a	7.90 ± 1.08^a	8.17 ± 1.17^a	8.05 ± 0.94^a	146
CS	6.19 ± 1.63^b	6.83 ± 1.71^a	6.55 ± 1.68^b	7.12 ± 1.61^b	6.76 ± 1.46^{bc}	95
CCH	6.83 ± 1.90^b	5.43 ± 2.20^b	6.71 ± 2.13^b	6.12 ± 2.13^c	6.21 ± 1.91^c	69
CC	6.79 ± 1.63^b	7.21 ± 1.63^a	7.10 ± 1.43^{ab}	7.69 ± 1.20^{ab}	7.24 ± 1.16^b	110

CON—control sample; CS—sponge cake with spirulina; CCH—sponge cake with chlorella; CC—sponge cake with cricket. In each column, values marked with the same letters do not differ significantly at $p < 0.05$ (Tukey's post hoc test).

The organoleptic evaluation of fortified products is essential because it helps determine whether a newly designed product is acceptable to consumers and can be launched on the market. It is particularly important in studies that fortify well-known foods with microalgae and edible insects, which are not usually consumed by Western populations [78]. Spirulina and chlorella have a strong green color and distinctive taste and aroma, which can be challenging for consumers. This was particularly evident in the sponge cake with chlorella, which received the lowest scores for aroma and taste. This is due to the high levels of aldehydes and ketones in chlorella, which impart a grassy, plant-like aroma [79]. However, there are several ways to address the specific microalgae smell. For fortified foods, masking with other flavors or encapsulation may be most effective [80]. The reason consumers rate the color of sponge cake lower may be their familiarity with the classic light color of this baked good and the fact that green is not associated with natural confectionery products. However, as other consumer studies show, depending on the food matrix used, adding spirulina can improve the color rating of the fortified product. For example, green pesto sauce with 1% *Arthrospira platensis* was rated higher for color than the classic, unfortified

sauce [16]. Like microalgae, insects offer numerous health benefits, but their consumption, especially in Western countries, is limited by frequent consumer rejection. This is influenced by many factors, including social influences and cultural norms, psychological factors, and limited consumer knowledge and awareness [16]. The studies presented used insect powder, which is generally more acceptable than whole insects, hence the high ratings for the product fortified with *Acheta domesticus*. Incorporating insect flour into widely consumed products, such as baked goods, is anticipated to help reduce food neophobia and enhance consumer acceptance of insects as part of the human diet [81].

4. Conclusions

The addition of spirulina, chlorella, and cricket powder significantly altered the properties of sponge cakes. The microalgae had the most pronounced effect on color, reducing lightness and shifting the hue towards green, whereas the insect powder produced only minor color changes. All additives increased protein content and levels of selected minerals, particularly magnesium (Mg), iron (Fe), and zinc (Zn). The protein additives used, particularly spirulina and cricket powder, significantly increased the protein content of the enriched products. This increase in protein content was accompanied by only minor changes in fat and carbohydrate levels, and no significant changes were observed in the products' total energy value. The antioxidant activity of the enriched samples was higher than that of the control, with cricket powder exhibiting the highest antioxidant potential, while spirulina contributed the most to increasing flavonoid content. Although the differences in predicted glycemic index (pGI) were relatively small, all fortified samples exhibited significantly lower pGI values than the control ($p < 0.05$). Sensory evaluation indicated that the microalgae reduced the product's overall appeal, primarily due to substantial changes in color and taste. Among the enriched variants, the sponge cake with cricket powder was the most acceptable, combining nutritional benefits with good sensory characteristics. In terms of application, cricket powder is the most promising functional additive, combining improved nutritional value and biological activity with acceptable sensory qualities. Although microalgae enhance mineral composition and antioxidant properties, their optimal dosage or combination with other ingredients is needed to minimize adverse effects on the sensory qualities of sponge cake.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ΔE	color difference
ABTS ^{•+}	2,20-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) radical
CC	sponge cake with cricket
CCH	sponge cake with chlorella
CON	control sample
CS	sponge cake with spirulina
DPPH [•]	2,2-diphenyl-1-picrylhydrazyl radical
FM	fresh material
GOPOD	glucose oxidase/peroxidase
HI	hydrolysis index of starch
pGI	predicted glycemic index
TEAC	Trolox Equivalent Antioxidant Activity
TFC	total flavonoid content
TPC	total phenolic content
WI	whiteness index

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