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Nutritional Composition and Functional Properties of Sacha Inchi Spent Flour

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ABSTRACT

Sacha Inchi (Plukenetia volubilis L.), also known as the Inca nut, is recognized as a sustainable crop rich in unsaturated fatty acids. Limited studies have explored the potential of Sacha Inchi spent (SIS) flour as a functional ingredient. This study evaluates the nutritional composition and physical-functional properties of SIS flour compared with high-protein wheat (HPW) flour and walnut flour. SIS flour exhibited high fat (41.0%), fibre (36.3%), and protein (52.8%) contents. The total phenolic content (13.4 mg GAE/g) and antioxidant inhibition (44.3%) indicate potential use as a natural antioxidant source. The flour also demonstrated the highest water absorption capacity (7.1 g/g) and potassium content (3.4 ppm). Overall, SIS flour is a promising functional ingredient suitable for nutritious, clean-label, and sustainable food applications.

Keywords: Sacha Inchi (*Plukenetia volubilis L.*), wheat flour, unsaturated fatty acids.

1. INTRODUCTION

The Inca nut, also known as Sacha Inchi (*Plukenetia volubilis L.*), belongs to the family Euphorbiaceae. It is a perennial, climbing, oleaginous plant native to the Amazon, producing star-shaped fruits that contain lenticular seeds arranged in groups of four, five, or six. Each seed consists of a single white cotyledon enclosed in a stiff, dark-coloured, nut-like seed coat (Sethuraman et al., 2020). During maturation, the fruits change from green to brownish-black, indicating ripening. Sacha Inchi is indigenous to the Peruvian jungle and also grows throughout the Andean region of South America. For more than 3,000 years, the Peruvian Incas have consumed Sacha Inchi seeds and oil as part of their diet. Today, the plant is also cultivated for economic purposes in Southeast Asia, particularly in Thailand and Myanmar (Kodahl & Sørensen, 2021). It thrives in the Amazonian forest at altitudes of 200–1,500 meters and is predominantly cultivated in southern Colombia and Peru due to its high commercial potential (Kim & Joo, 2019).

Sacha Inchi is considered an important component of a nutritious diet. Its seeds are used to produce oil and flour, but more commonly they are consumed roasted. Owing to their high omega-3, omega-6, and complete protein content, roasted Sacha Inchi seeds are regarded as a healthy snack. The seed oil is highly valued as a dietary supplement. Beyond the seeds, the leaves of the plant are also edible and can be cooked as part of traditional dishes. In traditional Peruvian diets, roasted seeds, seed oil, and cooked leaves are appreciated for their high nutritional value. Sacha Inchi can be consumed raw or cooked in various ways, including boiling and steaming.

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The seeds are rich in omega-3 and omega-6 fatty acids, as well as protein, fat, and fibre. They contain high levels of polyunsaturated fatty acids, are cholesterol-free, and provide antioxidants together with vitamins A and E. Sacha Inchi oil is especially valued due to its unusual fatty acid profile: omega-3 α-linolenic acid (45–53%), omega-6 linoleic acid (34–39%), and omega-9 (6–10%) (Sethuraman et al., 2020). The protein in Sacha Inchi is highly digestible (24–33%) and contains essential amino acids. The oil also has a high proportion of polyunsaturated fatty acids, low saturated fatty acid content, and negligible trans-fatty acids. The heart-shaped leaves contain beneficial compounds such as terpenoids, saponins, and phenolic compounds (flavonoids), making them safe for consumption.

In this study, the nutritional value of Sacha Inchi spent (SIS) flour was examined together with its physicochemical characteristics and antioxidant activity. This comprehensive investigation supports the potential development of value-added products derived from agricultural biomass using SIS flour.

2. MATERIALS AND METHODS

2.1 Materials

The Sacha Inchi seeds were procured from Delima Jelita Herbs Company (Alor Setar, Kedah, Malaysia). High-protein wheat flour (Prima Brand, Singapore) was purchased from Giant Hypermarket (Alor Setar, Malaysia). Analytical-grade methanol (≥99.9%, Merck, Darmstadt, Germany), gallic acid monohydrate standard (Sigma-Aldrich, St. Louis, MO, USA), sodium carbonate (Merck, Germany), and Folin–Ciocalteu reagent (Sigma-Aldrich, USA) were used in the assays. The instruments used included a UV–Vis spectrophotometer (Shimadzu UV-1800, Japan), a Chroma Meter (Konica Minolta CR-400, Japan), a centrifuge (Eppendorf 5804R, Germany), a grinder (Panasonic MX-AC400, Malaysia), a hotplate (IKA C-MAG HS7, Germany), and an Atomic Absorption Spectrometer (PerkinElmer AAnalyst 400, USA). Statistical analyses were conducted using SPSS software (Version 26.0; IBM Corp., Armonk, NY, USA).

2.2 Preparation of Sacha Inchi Spent Flour (SIS flour)

The raw Sacha Inchi seeds were cleaned to remove dirt and any foreign matter. The seeds were then dried and roasted at 170 °C for 10 minutes. The roasted seeds were pressed to extract the oil, and the resulting spent material was ground using an electric grinder. The SIS flour obtained was stored in airtight containers and kept in a refrigerator for further use.

2.3 Nutritional Composition – Proximate Analysis

Nutritional analysis of moisture (Method 925.40), ash (Method 923.03), fat (Method 920.39), protein using Lowry Method with minor modification (Abidin *et al.,* 2023) and crude fiber (Method 7.504) was determined according to the standard AOAC 1990 method. Carbohydrates have been calculated as formula below:

$$Carbohydrate = [100 - (moisture + protein + crude\ fat + ash + crude\ fiber)] \quad (1)$$

2.4 Total Phenolic and Antioxidant Content

First, 1 g of each flour sample was extracted for 4 hours with 100 mL of methanol at 40 °C using a shaking water bath with continuous stirring at 150 rpm. The extract was then filtered under vacuum and chilled to room temperature before being frozen at –20 °C. All extractions were performed in triplicate.

The Folin–Ciocalteu reagent was used to determine the total phenolic content. For this analysis, 0.2 mL of the plant extract was mixed thoroughly with 0.2 mL of Folin–Ciocalteu reagent in a test tube. After 4 minutes, 1 mL of sodium carbonate solution (15% w/w) was added, and the mixture was allowed to stand for 2 hours at room temperature (25 °C). The absorbance of the sample was then measured using a UV–Vis spectrophotometer, and the total phenolic content (TPC) was calculated based on a gallic acid monohydrate standard curve (Zugazua-Ganado et al., 2024). All measurements were performed in triplicate.

For the antioxidant assay, a 60 μM DPPH working solution was prepared by diluting 15 mL of a 1 mM DPPH stock solution to 250 mL with ethanol (Baliyan et al., 2022). The control was prepared by mixing 200 μL of ethanol with 2500 μL of the 60 μM DPPH solution in a cuvette and incubating the mixture in the dark for 30 minutes. For sample analysis, 200 μL of each flour extract was mixed with 2500 μL of the DPPH solution and incubated under identical conditions. Absorbance was measured at 517 nm using a UV–Vis spectrophotometer, and the DPPH radical scavenging activity (%) was calculated accordingly.

2.5 Color Analysis

Random samples were taken in triplicate for both SIS and high-protein wheat (HPW) flours. Two tablespoons of each flour were used to determine colour values using a Chroma Meter (Konica Minolta CR-400, Japan). Measurements were recorded based on the CIE Lab* colour space, where L* represents lightness, a* represents redness, and b* represents yellowness (Shi et al., 2024).

2.6 Bulk Density and Water Absorption Capacity Analysis

Bulk density was determined by weighing approximately 2 g of each flour sample into a 10 mL graduated cylinder. The cylinder was gently tapped on a laboratory bench several times until the sample level no longer decreased. The final volume occupied by the flour in the graduated cylinder was then recorded (Bala et al., 2020).

According to Zhang et al. (2023), the centrifugation method was used to determine the water absorption capacity (WAC). Three grams of each sample were mixed with 25 mL of distilled water and transferred into pre-weighed centrifuge tubes. The mixture was intermittently stirred for 30 minutes before being centrifuged at 3000 g for 25 minutes. The supernatant was decanted, and the tubes were inverted and allowed to drain for 25 minutes at room temperature to remove excess moisture. The samples were then reweighed. Water absorption capacity (WAC) was expressed as the grams of water absorbed per gram of dry material.

2.7 Oil Absorption Capacity

In pre-weighed centrifuge tubes, 0.5 g of each sample was combined with 6 mL of corn oil. The mixture was swirled for 1 minute to ensure proper dispersion of the sample in the oil. The tubes were then allowed to stand for 30 minutes before centrifugation at 3000 g for 25 minutes (Wang et al., 2020). After centrifugation, the separated oil was removed using a pipette, and the tubes were inverted for 25 minutes to allow excess oil to drain. The samples were then reweighed. Oil absorption capacity (OAC) was expressed as the grams of oil absorbed per gram of dry material.

2.8 Potassium Concentration

The sample was prepared using the wet ashing method. Two grams of homogenized sample were placed in a digestion vessel, followed by the addition of 20 mL of 65% nitric acid and 10 mL of 70% perchloric acid. The acidified samples were allowed to digest at room temperature for 24 hours. After digestion, the samples were heated on a hotplate at 120 °C until the solution reached a gentle boil and continued simmering until it became transparent. This process typically required one hour or longer, depending on the sample. Each digested sample was then filtered through Whatman No. 42 filter paper, and the filtrate was diluted to 100 mL with deionized distilled water, Potassium (K) concentration was determined using atomic absorption spectroscopy at a wavelength of 766.5 nm and a slit width of 0.7 nm. All samples and standards were analyzed in triplicate.

2.9 Statistical Analysis

The results were statistically analyzed using SPSS (SPSS Inc., Chicago, USA). Analysis of variance (ANOVA) was used to determine significant difference between the results and Duncan's test was used to separate the mean with a significance level of 0.05.

3. RESULTS AND DISCUSSION

3.1 Nutritional Composition of the Flours

The SIS flour had an average moisture content of 2.1% ± 0.1, whereas the HPW flour had a significantly higher moisture content of 11.7% ± 1.5. For comparison, walnut flour showed an average moisture content of 8.8% ± 0.2 (Liu et al., 2021).

Table 1: Nutritional Composition of HPW and SIS flours (g/100g dry sample)

Composition	HPW Flour (%)	SIS Flour (%)	Walnut Flour (%) (Liu et al., 2021)
Moisture	11.7 ± 1.5^{a}	2.1 ± 0.1^{c}	8.8 ± 0.2^{b}
Ash	1.6 ± 1.0^{c}	2.4 ± 0.0^{b}	5.5 ± 0.1^{a}
Fat	4.7 ± 0.7^{b}	41.0 ± 1.7^{a}	2.0 ± 0.0^{c}
Fiber	8.7 ± 0.3^{b}	36.3 ± 0.2^{a}	4.0 ± 0.3^{c}
Protein	27.4 ± 0.6^{c}	52.8 ± 0.7^{a}	38.1 ± 0.1^{b}
Carbohydrate	54.3 ± 7.3^{a}	1.6 ± 7.2^{c}	45.6 ± 0.8^{b}

(Note: All values are reported as mean values on a dry weight basis ± standard deviation (n=3). Values in the same row followed by different letter are significantly different ($p<0.05$).)

The results show that the moisture content of SIS flour was significantly lower than that of high-protein wheat flour ($p < 0.05$). This is attributed to the roasting process used during SIS flour preparation, which naturally reduces moisture compared with HPW and walnut flour. Moisture levels below 10% are generally recommended to reduce microbial growth and extend the shelf life of dry flours; therefore, the low moisture content of SIS flour is advantageous for storage stability.

Based on Table 1, the ash content of HPW flour was 1.6% ± 1.0, SIS flour was 2.4%, and walnut flour was 5.5% ± 0.1 (Liu et al., 2021). The variation in these values may be influenced by factors such as soil composition, genetic characteristics of the cultivated plants, and the plants' nutrient absorption capacity (Silver et al., 2021). Among the samples, walnut flour had the highest ash content, indicating a higher mineral concentration, while HPW flour had the lowest due to its reduced ash content. HPW also showed significantly lower mineral content compared with SIS flour. Generally, the mineral content of foods is expected to be around 5%, and therefore, the values obtained in this study fall within the acceptable range.

Among the samples analyzed, SIS flour exhibited the highest average fat content at 41%. This value was significantly higher ($p < 0.05$) than that of HPW flour (4.7%) and walnut flour, which had the lowest fat content at 2%. The high fat content in SIS flour is expected because the Sacha Inchi seeds used in its preparation were roasted but not defatted, allowing much of the natural oil to remain. In contrast, HPW flour is commercially processed and thus contains substantially less fat. Sacha Inchi seeds generally contain up to 97.2% natural lipids and possess an omega-6:omega-3 fatty acid ratio ranging from 0.81 to 1.12, close to the ideal 1:1 ratio recommended for human health (Simopoulos, 2011). Walnut flour showed the lowest fat content because the sample used by Liu et al. (2021) was defatted during processing.

Among all the flour samples, SIS flour exhibited the highest crude fibre content, averaging 36.3%. This was followed by HPW flour with an average of 8.7% and walnut flour with a relatively low average of 4% (Labuckas et al., 2014). Thus, SIS flour contained significantly higher fibre than HPW flour. The high fibre content in SIS flour is attributed to its low carbohydrate proportion and the roasting process, which concentrates fibre components. In contrast, the removal of wheat bran during the milling of HPW flour contributes to its lower crude fibre level. A similar explanation applies to walnut flour, where the milling and defatting processes reduce fibre content. Given that fibre is digested slowly and contributes to better satiety and digestive health, SIS flour may serve as a suitable ingredient for producing healthier baked products such as bread.

Based on nitrogen content obtained, SIS flour has a significantly higher crude protein content average of 52.8% when compared to HPW flour, followed by walnut flour at an average of 38.1% according to Labuckas et al. (2014). Even with high protein added in HPW flour, HPW flour has the lowest crude protein content at an average of 27.4%. If normal wheat flour used for this evaluation, the protein content would be lower. The value of SIS flour is comparable with the protein value of commercial Sacha Inchi (56.53%) from Amazon Health Products that was made using *Plukenetia volubilis* which is the same type as the raw material used for SIS flour (Gonzales et al., 2018).

Protein content of SIS flour greatly affect by its processing method. This is because when compared to protein content of Sacha Inchi's raw unprocessed seed, it has low protein content, between 22-30% (Kodahl & Sørensen, 2021). So, roasting method increased the protein content of SIS flour. Both HPW and walnut flour were already processed and defatted making the fiber content lower during the flour milling. It is essential that the flours has a high value of protein because it is the most significant nutrient in the diet, allowing for greater control over the quality of food purchased or supplied using SIS flour.

HPW flour has the highest carbohydrate of 54.3%, followed by walnut flour at an average of 45.6%. SIS flour has the lowest carbohydrate percentage of only 1.6%. So, HPW has relatively higher carbohydrate than SIS flour. The carbohydrate in SIS flour were greatly impacted by high protein, fat and fiber. This could also explain why HPW and walnut has high carbohydrate since they both have low protein, fat and fiber content. As a comparison from Goyal et al. (2022), Sacha Inchi seed has the lowest carbohydrate in between 6.00-30.90 g/100g when compared to flaxseed (27.90-38.10 g/100g) and chia seed (26.90-42.10 g/100g). In agreement with Sethuraman et al. (2020), Sacha Inchi also has lower carbohydrate content at 3.1 g and walnut with slightly higher at 3.8g.

3.1.1 Mineral Analysis (Potassium)

Generally, SIS flour contains the highest levels of potassium (K), followed by manganese (Mn) and phosphorus (P) (Sethuraman et al., 2020). This is supported by the results in Table 2, where SIS flour showed a significantly higher potassium content of 3.4 ppm, compared with walnut flour at 0.8 ppm. The potassium content in HPW flour was below the detection limit, resulting in a negative apparent reading, likely due to inherently low potassium levels and instrument baseline variability. The elevated potassium content in SIS flour is attributed to the roasting process used during preparation, whereas the lower potassium levels in walnut and HPW flours may result from milling, defatting, and other processing steps that reduce mineral content (Sethuraman et al., 2020).

Consistent with previous findings, roasted Sacha Inchi samples retain significantly higher potassium levels than boiled samples, indicating that roasting is an effective method for enhancing potassium concentration. Potassium is essential for maintaining cellular water balance and supporting protein and carbohydrate metabolism (Kim & Joo, 2019). Walnut flour is also considered a good potassium source, as potassium is one of its predominant minerals (Rabadán et al., 2018). Overall, compared with other common nuts, Sacha Inchi products may serve as an excellent source of dietary potassium.

Table 2: Concentration of Potassium in the Flours

Flour Type	Concentration of Potassium (K, ppm)
HPW Flour	ND
SIS flour	3.4 ± 0.1[a]
Walnut Flour	0.8 ± 0.1[b]

(Note: All values are reported as mean values on a dry weight basis ± standard deviation (SD) (n=3). ND is Not Detected, Values in the same column followed by different letter are significantly different ($p<0.05$).)

3.2 Total Phenolic Content (TPC) and Antioxidant Activity

Due to the roasting method used during SIS flour processing, it exhibited a significantly higher total phenolic content (TPC) compared with HPW flour and walnut flour. As shown in Table 3, the TPC values were 13.4 mg GAE/g for SIS flour, 6.1 mg GAE/g for HPW flour, and 2.9 mg GAE/g for walnut flour (dry weight basis) (Labuckas, 2014).

Table 3: Total Phenolic Content and Antioxidant Activity of the Flours

Composition	HPW Flour	SIS flour	Walnut Flour
Total Phenolic Content (mg GAE/g)	6.1 ± 0.4[b]	13.4 ± 2.2[a]	2.9 ± 0.2[c]
Inhibition (%)	10.9 ± 2.1[c]	44.3 ± 4.9[b]	56.4 ± 5.1a

(Note: All values are reported as mean values on a dry weight basis ± standard deviation (n=3). Values in the same row followed by different letter are significantly different ($p<0.05$).)

According to Wang et al., (2018), almonds and pine nuts had lower TPC than Sacha Inchi seeds. However, Sacha Inchi seeds have a lower TPC than several common nuts such as walnuts, and pistachios. HPW flour has lower TPC because wheat usually has lower phenolic content than fruits or seeds, so it was expected for HPW to have lower phenolic content than SIS flour.

The ability of the extracts to scavenge DPPH radicals is a key indicator of their antioxidant activity, expressed as the percentage of inhibition. Based on the free radical scavenging activity, SIS flour demonstrated an inhibition rate of 44%. According to Hernández-Parra et al. (2025), the type of heat treatment applied to Sacha Inchi seeds significantly influences their antioxidant properties. Seeds exposed to thermal treatments with low water activity, such as high-temperature roasting or honey roasting, tend to lose a greater proportion of their antioxidant capability.

As shown in Table 3, walnut flour exhibited the highest inhibition value (56.4%), followed by SIS flour (44.3%), while HPW flour displayed the lowest antioxidant activity (10.9%). The significantly higher antioxidant inhibition percentage in SIS flour compared with HPW flour corresponds with its higher total phenolic content (TPC), since phenolics contribute substantially to antioxidant capacity. In addition, the higher fat content in SIS flour relative to HPW flour may also contribute to its greater antioxidant potential. Walnut flour showed slightly higher antioxidant activity than SIS flour, likely due to the characteristics of the defatted walnut flour used in the comparison.

3.3 Functional Properties

Bulk density is an important characteristic of flour because it influences packaging efficiency and ease of handling during transportation. Flours with higher bulk density can be packed more tightly, allowing for improved storage and transport of larger quantities (Forsido et al., 2021). As shown in Table 4, HPW flour exhibited a significantly higher bulk density (67.6 g/mL) compared with SIS flour (52.7 g/mL).

Table 4: Physical Compositions of the Flours

Compositions	HPW Flour	SIS flour	Walnut Flour
Bulk density (g/ml)	67.6 ± 0.4[a]	52.7 ± 1.6[b]	ND
Water absorption capacity (WAC) (g/g)	1.4 ± 0.1[c]	7.1 ± 0.1[a]	5.6 ± 0.4[b]
Oil absorption capacity (OAC) (g/g)	1.2 ± 0.1[c]	2.7 ± 0.4[b]	4.4 ± 0.1[a]

(Note: All values are reported as mean values on a dry weight basis ± standard deviation (n=3). Values in the same row followed by different letter are significantly different ($p<0.05$). The values of walnut flour are derived from Labuckas et al., (2014). ND = No Data.)

No data were obtained for the bulk density of walnut flour; however, it is expected to fall within the range of HPW flour, as walnut flour is also processed and defatted. SIS flour, on the other hand, exhibited a lower bulk density because its particles are slightly larger and coarser than those of refined HPW flour (Bala et al., 2020). Variations in bulk density among different flours are often attributed to differences in starch concentration. In general, higher starch content increases bulk density, as starch granules contribute to tighter packing (Hasmadi et al., 2020).

The WAC of SIS flour was found to be significantly higher than HPW flour. The WAC value of SIS flour, walnut flour and HPW flour were 7.1 g of water/g, 5.6 g of water/g and 1.4 g of water/g respectively. The high WAC observed may be attributed to the elevated fiber content, which enhances its ability to retain water through hydrophilic interactions (Labuckas et al., 2014). The findings showed that fibers could help with hydration, which is thought to be due to the hydroxyl groups in the fiber structure, allowing for additional water interactions through hydrogen bonding (Renzetti et al., 2025). As a result, SIS flour could be a valuable thickening agent or functional agent in food systems like bakery products, where hydration qualities are needed to prevent staling and boost food stability (Labuckas et al., 2014).

According to Wang et al. (2020), oil absorption capacity (OAC) is an important functional property because it enhances mouthfeel and improves flavour retention in food products. A higher OAC value generally indicates better flavour-binding ability. As shown in Table 4, walnut flour exhibited the highest OAC (4.4 ± 0.1 g oil/g), followed by SIS flour (2.7 ± 0.4 g oil/g) and HPW flour (1.2 ± 0.1 g oil/g). An increase in OAC is often associated with the exposure of buried hydrophobic groups during processing, such as in protein hydrolysates. When more hydrophobic groups become available, their interaction with oil increases, resulting in higher OAC values (Jin et al., 2020). The presence of non-polar side chains, which can bind to hydrocarbon groups in oils, also contributes to increased oil absorption in flours.

Flours with high OAC values can be advantageous in various food applications because they enhance structural integrity, improve palatability, extend shelf life, and help retain flavour—particularly in meat and bakery products where fat absorption is desired (Hasmadi et al., 2020). A protein's ability to bind oil and water depends on intrinsic characteristics such as its structural conformation, amino acid composition, and surface polarity or hydrophobicity (Zhang et al., 2022). Due to these properties, flours with high OAC are commonly used in products such as sausages, whipped toppings, angel and sponge cakes, and chiffon desserts.

3.4 Colour Analysis

The colour of the samples is shown in Figure 1. SIS flour appeared noticeably darker than both HPW and walnut flours, which is attributed to the roasting process used during its preparation. In contrast, HPW and walnut flours were lighter in colour because they undergo bleaching and other processing steps prior to commercial distribution.

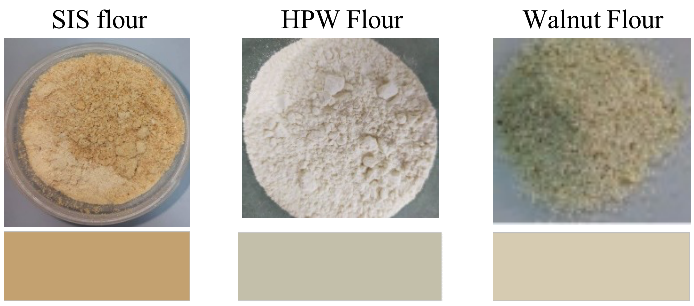

Figure 1: Colour of the flour samples

Table 5 presents the colour analysis of SIS flour, with HPW flour used as the control. Walnut flour recorded the highest L* value (82.1), indicating it was the lightest among all samples, while SIS flour was the darkest with an L* value of 68.6. HPW flour showed a slight green hue, reflected by its negative a* value (−1.27), whereas SIS flour exhibited the highest redness with an a* value of 8.0, followed by walnut flour. SIS flour also displayed the highest yellowness, with a b* value of 30.8, compared with walnut flour (14.3) and HPW flour (11.0).

Table 5: CIE L*a*b* Colour Profile Analysis of the Flour Samples

Indicator	HPW Flour	SIS flour	Walnut Flour
L*	77.2 ± 3.4[b]	68.6 ± 0.5[c]	82.1 ± 0.9[a]
a*	-1.27 ± 0.9[c]	8.0 ± 0.4[a]	0.8 ± 0.2[b]
b*	11.0 ± 5.5[b]	30.8 ± 0.5[a]	14.3 ± 0.6[b]

(Note: All values are reported as mean values on a dry weight basis ± standard deviation (n=3). Values in the same row followed by different letter are significantly different (p<0.05).)

4. CONCLUSION

The present study demonstrated that SIS flour is a valuable by-product with notable nutritional and functional properties, containing substantial levels of protein, dietary fibre, and essential minerals that highlight its potential as a sustainable ingredient for food fortification. Its favourable water and oil absorption capacities enhance texture, moisture retention, and stability in various food formulations, while residual phenolic compounds contribute to moderate antioxidant activity with potential health benefits. Moreover, the utilisation of SIS flour supports SDG 12: Responsible Consumption and Production, as it promotes the valorisation of agricultural by-products and advances zero-waste, sustainable food system initiatives. Overall, SIS flour represents a promising functional ingredient for the development of nutrient-dense, clean-label, and environmentally responsible food products.

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