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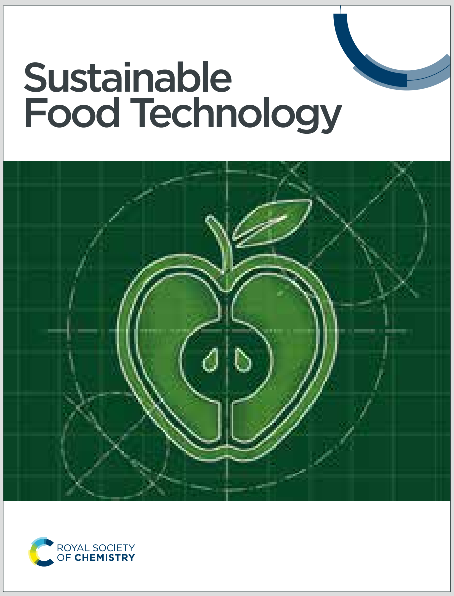

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Sustainability spotlight statement

This study valorizes purple sweet potato peel, an accessible post-processing by-product, into a functional pasta ingredient, exemplifying circular bioeconomy and waste-to-value principles. Partially replacing wheat flour with sweet potato peel powder in pasta offers a scalable way to boost dietary fiber and antioxidants while lowering glycemic impact, promoting healthier nutrition diets. The approach aligns with sustainability by focusing on post-harvest valorization, supply chain efficiency, and environmentally conscious practices. Sustainability benefits include reducing organic waste and landfill pressure, avoiding disposal emissions, and saving energy through shorter cooking times. The study demonstrates how by-product extraction and process intensification can provide safe, high-quality foods with environmental, economic, and health advantages co-benefits.

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Potential of purple sweet potato (Ipomoea batatas L.) peel powder to enhance textural, cooking, and sensory quality, glycemic index, and antioxidant bioaccessibility of fiber-enriched pasta

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Purple sweet potato peel (*Ipomoea batatas* L.), a by-product of processing, is a potential source of dietary fiber and bioactive compounds. This study aimed to utilize locally available sources of purple sweet potato peel powder (SPP) as a dietary fiber and antioxidant source that was blended with durum wheat semolina (DWS) in pasta making. Compared to the control, pasta incorporating the highest SPP level of 40% SPP showed significant improvements in phytochemicals and fiber, with increases of 6.3, 4.6, and 31.1-fold in dietary fiber, phenolics, and flavonoids respectively. No anthocyanins were detected in the control samples, but inclusion of 40% SPP in the pasta formulation resulted in an anthocyanin content of 49 mg C3GE/100 g dw. The increased levels of SPP considerably decreased the optimal cooking time and swelling capacity of pasta but led to an increase in cooking loss. The textural attributes were increased in terms of firmness, hardness, gumminess, and chewiness, while demonstrating reduction in cohesiveness, tensile strength, and elongation rate. The pasta fortified with 10 to 30% SPP fell within the medium glycemic index (GI) category while the pasta supplemented with 40% SPP was classified as belonging to the low GI group. In contrast, the control exhibited a high GI food of 71.1. The bioavailability of phenolic compounds, flavonoids, and anthocyanins increased by 2.1- to 3.3-fold as the SPP supplementation ratio was elevated from 10% to 40%. These enhanced bioactive compounds likely contributed to the increased release of antioxidant activities during digestion, with the pasta containing 40% SPP replacement demonstrating the highest proportion of antioxidant activity.

Introduction

Millions of tons of by-products, including seed, skin, pod, peel, and pomace, are daily generated by the vegetable processing industry. This phenomenon has emerged as a significant global concern due to its detrimental effects on the environment, as well as the social and economic sectors. Nevertheless, numerous by-products are rich in essential nutrients, including proteins, sugars, and lipids; they also contain dietary fibers, and bioactive compounds such as terpenoids, phenolics, and alkaloids which are beneficial for human health [1]. Therefore, vegetable by-products can be utilized as functional ingredients in various types of foods, such as bread, cookies, brownies, muffins, yogurt, cheese, and salad dressing [2].

Purple sweet potato (Ipomoea batatas L.) belongs to the genus Ipomoea, abundant in Central America. Today, purple sweet potato has gained popularity in various countries such as China, India, the Philippines, Indonesia, Vietnam, Uganda, Spain, and Portugal, attributable to their high levels of productivity and extensive adaptability [3]. Purple sweet potato has been utilized in the food industry to produce purple sweet potato powder, beverages, canned and frozen products, which result in the generation of large amount of purple sweet potato peel [4]. Every 50 kg of purple sweet potato will produce about 3 kg of sweet potato peel [5]. In 2019, approximately 240,000 kg of purple sweet potato peel was discarded from 4 million kg of purple sweet potato [6]. It is reported that purple sweet potato peel contains a diverse array of nutritional constituents, including essential vitamins and minerals [7]. Notably, it is rich in dietary fiber, consisting of both soluble dietary fiber (SDF) and insoluble dietary fiber (IDF), which enhances its functional properties [8]. These fibers can significantly influence metabolites involved in the regulation of human metabolism [9]. Furthermore, the peel of purple sweet potato also contains bioactive compounds, including anthocyanins, phenolic acids, and tannins, all of which possess significant antioxidant capabilities and a potential lowering effect on glucose levels associated with diabetes [10]. Therefore, purple sweet potato peel, an abundant and underused by-product rich in dietary fiber and antioxidants, was chosen to valorize waste and create high-fiber, antioxidant-rich pasta with potential glycemic benefits. Purple sweet potato peel powder (SPP) has been employed in the formulation of high fiber- and antioxidant-enhanced bakery products such as biscuits, muffins, and cupcakes [7,11,12]. Nevertheless, its

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application in the development of pasta products remains largely unexplored in the literature.

Pasta ranks among the most widely consumed products on a global scale, largely due to its versatility and convenience. The integration of vegetable and fruit by-products into pasta products represents a significant trend that garners considerable interest among consumers [13]. Recently, the incorporation of mango peel powder [14], pomegranate peel powder [15] and banana peel powder [16] into the pasta formulation significantly enhances dietary fiber, phenolic, and micronutrient contents along with antioxidant capacities of the fortified pasta. The incorporation of plant materials into pasta reduces the digestion of starch due to the inhibitory effects of phenolic compounds on carbohydrate digestive enzymes [17]. Furthermore, incorporating fruits and vegetables by-products into pasta enhances the shelf-life of fresh pasta [18]. Pasta was selected for this study due to its widespread consumption and standardized nature, which ensures the preservation of bioactive compounds and facilitates slower starch digestion. This characteristic makes it an optimal carrier for fortification with purple sweet potato peel. Furthermore, to the best of our knowledge, no prior research has incorporated purple sweet potato peel into pasta, thereby introducing a novel aspect to this investigation.

This research focused on the utilization of by-products from the food industry to address the demand for fiber- and antioxidant-enhanced foods that promote human health and mitigate the waste associated with purple sweet potato peel. It aimed to evaluate the effects of purple sweet potato peel on nutritional quality, cooking properties, physical characteristics, and overall acceptability of the fortified pasta. Furthermore, the antioxidant bioaccessibility and glycemic index of the fiber-enriched pasta with different peel levels were also evaluated through an *in vitro* test.

Materials and methods

Materials.

Purple sweet potato (*Ipomoea batatas* L.) peel was collected at a local agricultural product processing enterprise (Ho Chi Minh City). Semolina durum flour was originated from Divella (Rutigliano, Bari, Italy). Refined table salt was provided by Southern Salt Group (Ho Chi Minh City).

Analytical chemicals

Enzyme preparations, including α-amylase, glucoamylase, and protease, were purchased from Novozymes Company (Bagsværd, Denmark) and used for dietary fiber analysis. Analytical chemicals including 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,4,6-tri(2-pyridyl)-s-triazine, 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox), gallic acid (GA), 2-(3,4-dihydroxyphenyl)-3,5,7-trihydroxy-4H-1-benzopyran-4-one, Folin–Ciocalteu reagent, 3, 3′,4′,5,6-pentahydroxyflavone (quercetin), porcine gastric pepsin, pancreatin from pig pancreas were supplied by Sigma-Aldrich (St. Louis, Missouri, USA), while organic solvent were obtained from Chemsol (Ho Chi Minh City, Vietnam).

Preparation of SPP

Purple sweet potato peel was meticulously washed with tap water to eliminate mechanical impurities. Following the washing process, the peel was subjected to drying in a convective dryer (SF30, Memmert, Büchenbach, Germany) at a temperature of 55 °C until their moisture content of 10-13% was attained. The resulting dried peel was pulverized and sieved through a 70-mesh (0.21 mm) screen. The obtained SPP powder was packed in polyethylene bags and stored at 4 °C for subsequent experiments.

Pasta preparation

Durum wheat semolina was partially substituted with SPP in the pasta recipe. Pasta samples were labeled as Control, K10, K20, K30, and K40, representing SPP ratios of 0, 10, 20, 30, and 40% of the flour blend, respectively. The pasta formula included 300 g flour blend, and 1.5 g table salt. This mixture was well stirred for 5 min. Then, 160 mL water at 42 °C was added, and the dough was kneaded at 120 rpm for 20 min using a dough kneader (Professional, KitchenAid, Benton Harbor, Michigan, US). Pasta strands were produced by feeding the dough into an extruder (HR2365/05, Philips, Amsterdam, Netherlands). The extrusion pressure and mold diameter were 70.6 MPa and 1.6 mm, respectively. The extruded pasta was dried in a convection dryer (DL12-PTN, Tung Viet Ltd., Ho Chi Minh City, Vietnam) with hot airflow at 50 °C and 60% relative humidity for about 8 h to achieve a final moisture content of 11–12%. Dry pasta was stored at 4 °C for a maximum of one week for analysis.

Proximate composition

Total dietary fiber (TDF), insoluble dietary fiber (IDF), and soluble dietary fiber (SDF) were determined in accordance with 985.29, 991.42, and 991.43 methods, respectively established by the Association of Official Analytical Chemists (AOAC). Total protein and starch were measured using AOAC 984.13 and AOAC 996.11 methods, respectively, while lipid was quantified through Soxhlet extraction according to AOAC 960.39 method. Ash was analyzed using AOAC 9930.30 method. Moisture content was assessed using a moisture analyzer following drying at 105 °C (A&D Co., Tokyo) Japan).

Total phenolic, flavonoid and anthocyanin contents, and antioxidant capacities

About 1 g of SPP, durum wheat semolina, or milled pasta samples was added into 10 mL of 70% aqueous ethanol for antioxidant extraction, which was performed at 30 oC for 30 min. The extract was recovered by centrifugation at 1500×g for 20 min (DM0412, DLAB, Beijing, China). The obtained supernatant was used for analysis of total phenolic, flavonoid, and anthocyanin contents and antioxidant capacities. Total phenolic content (TPC) was assessed using the Folin-Ciocalteu method, as detailed by Agbor et al. (2014) [19]. Total flavonoid content was measured using the Aluminum Chloride ($AlCl_3$) method [20]. Total anthocyanin content was quantified through

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spectrophotometric analysis using the pH differential method, which leverages the color change of anthocyanins with pH [21]. Antioxidant capacities were evaluated using the DPPH free radical scavenging assay [22] and the ferric reducing antioxidant power (FRAP) assay [23].

Cooking properties

Pasta samples were cooked and used for evaluation of optimal cooking time (OCT), swelling index (SI), cooking loss (CL), and water absorption index (WAI) according to the procedure reported by Nguyen et al. [24].

Instrumental color

Instrumental color including lightness (L*), redness (a*), and yellowness (b*) was measured by using a Konica Minolta CR400 Chromameter (Osaka, Japan). Total color differences (ΔE) between the control and fortified pasta samples was calculated according to the formula described elsewhere [24].

Textural properties

Textural characteristics of pasta samples being cooked for their optimal durations, were determined utilizing a TA-XT plusC texture analyzer (Stable Micro Systems Co., Godalming, UK) in conjunction with the Windows version of Exponent Connect Lite 7.0 (Texture Technologies Co., Hamilton, MA, USA). Hardness, chewiness, tensile strength, and elongation rate of the pasta samples were recorded following the procedure described by Nguyen et al. (2020) [24].

Overall acceptability

Overall acceptability of pasta was evaluated with 60 untrained participants (both male and female aged from 18 to 50) recruited from Ho Chi Minh City University of Technology. Participants were selected based on their criterion of having consumed pasta at least once a week. Each pasta sample was coded with three digits. All pasta samples were cooked to their optimal cooking times and evaluated for their overall acceptability based on a 9-point scale, from 1-point (extremely disliked) to 9-point (extremely liked) [24].

Predicted glycemic index

In vitro digestion of cooked pasta samples was simulated by using enzymatic treatment with pepsin, pancreatin, and amyloglucosidase to break down starch into simpler sugars. The reducing sugar content was quantitatively assessed at specific time intervals using the 3,5-dinitrosalicylic acid (DNS) reagent, with measurements performed every 30 min for 3 h. The *in vitro* glycemic index was estimated using the method described by Werner et al. (2011) [25].

Antioxidant bioaccessibility

Pasta digestion was simulated by sequentially exposing samples to simulated gastric, and intestinal conditions, incorporating pH adjustments and enzymatic treatments with pepsin, pancreatin, and bile salts to replicate the human gastrointestinal environment. After digestion, the samples were centrifuged, and the supernatant was analyzed for phenolic, anthocyanin, and flavonoid contents, and antioxidant capacities. Pasta samples were *in vitro* digested using the methodology outlined by Werner et al. (2011). The antioxidant bioaccessibility was shown as the ratio between the quantity of substance released at the small intestine phase and the initial quantity present in the sample at the start of digestion [25].

Statistical analysis

Each pasta sample was conducted with three replicates, and the results were expressed as the mean value ± standard deviation (n = 3). One-way analysis of variance (ANOVA) and Turkey's post hoc test with $p < 0.05$ were utilized to assess the differences between variables using Minitab 16 software (Minitab Co., State College, PA, USA). Correlation coefficients using Pearson`s method were also calculated.

Results and discussion

Effects of supplementation ratio on nutritional quality of pasta

The chemical composition of SPP and DWS revealed notable distinctions, as illustrated in Table 1. The protein, lipid, and starch contents in SPP were 3.2, 2.1, and 2.2 times lower, respectively, than those found in DWS. In contrast, the total fiber content of SPP was 13.6 times greater than that of DWS. The total fiber content of SPP exceeded that of various by-products, including mesquite peel (25.7%), and peach peel (30.7-36.0%) [26]. SDF offers various health benefits, including hypoglycemic, antioxidant, and hypolipidemic effects, in addition to supporting the balance of gut microflora [27–30]. In contrast, IDF principally functions to enhance fecal bulk and relieve constipation [31]. Notably, the SDF/TDF ratio of SPP was approximately 26%, which was much higher than that of many common fiber sources, including apple peels (13%) [32] and orange peels (20%) [33]. The elevated ratio of SDF to TDF proves advantageous in ameliorating intestinal barrier functionality, enhancing short-chain fatty acid synthesis, and improving intestinal microbiota composition [34]. To be classified as high-quality dietary fiber, the proportion of SDF in TDF must be no less than 10% [27]. Furthermore, a SDF/IDF ratio is equal to or greater than 25% is beneficial for the proliferation of intestinal bacteria [35]. Due to high SDF/TDF ratio, SPP distinguished itself as a promising by-product for the development of fiber-rich food.

Pasta incorporated with 0 to 40% SPP exhibited significant changes in nutritional quality. Increasing the supplementation ratio from 0 to 40% reduced protein, lipid and starch levels of pasta by 39, 50, and 22%, respectively. However, the SPP-incorporated pasta showed impressive levels of dietary fiber. The TDF of pasta added with 10% SPP (the sample with the lowest SPP ratio) was recorded at 8.1 ± 0.5 (% dw), which exceeded the high-fiber food benchmark of 6.0 (% dw) [36]. As a result, pasta supplemented with SPP at a level of 10% or more was classified as a high-fiber food. Many studies demonstrate that high fiber consumption significantly reduces the risk of diabetes [37], digestive disorders (He et al. 2022), and colorectal carcinoma [38]. Moreover, as the proportion of SPP varied from

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10% to 40%, the SDF/TDF ratio exhibited a significant alteration, varying from 17 to 26%. The SDF/TDF ratio of 25% is crucial for deriving health benefits from dietary fiber, promoting the healthy physiological effects of both soluble and insoluble fiber [39]. It can be inferred that SPP serves as a viable source of dietary fiber for high-fiber pasta, as the resulting product achieves a satisfactory SDF/IDF ratio.

Table 1 Proximate composition of purple sweet potato peel powder (SPP), durum wheat semolina (DWS) used for pasta making and pasta samples supplemented with purple sweet potato peels powder (SPP)

Proximate composition	SPP	DWS	Control	K10	K20	K30	K40
Protein (%/dw)	3.8 ± 0.5^{b}	12.3 ± 0.7^{a}	12.2 ± 0.8^{a}	10.9 ± 0.4^{b}	9.6 ± 0.3^{c}	8.7 ± 0.1^{d}	7.5 ± 0.4^{e}
Lipid (%/dw)	1.3 ± 0.3^{b}	2.7 ± 0.3^{a}	2.6 ± 0.2^{a}	2.3 ± 0.1^{b}	1.9 ± 0.2^{c}	1.6 ± 0.1^{d}	1.3 ± 0.1^{e}
Ash (%/dw)	5.4± 1.0^{b}	0.6 ± 0.1^{a}	0.5 ± 0.1^{e}	1.7 ± 0.2^{d}	2.4 ± 0.2^{c}	3.2 ± 0.2^{b}	3.9 ± 0.3^{a}
Starch (%/dw)	35.2 ± 2.2^{b}	76.2 ± 3.0^{a}	75.8 ± 1.5^{a}	69.5 ± 1.3^{b}	66.1 ± 0.9^{c}	62.9 ± 0.7^{d}	59.5 ± 1.0^{e}
TDF (%/dw)	43.7 ± 3.2^{b}	3.2 ± 0.8^{a}	1.9 ± 0.7^{a}	6.7 ± 1.2^{b}	9.4 ± 1.0^{c}	12.4 ± 1.0^{d}	13.9 ± 0.8^{e}
IDF (%/dw)	32.5 ± 2.3^{b}	1.9 ± 0.5^{a}	1.2 ± 0.2^{a}	1.4 ± 0.1^{b}	2.3 ± 0.3^{c}	2.9 ± 0.2^{d}	5.0 ± 0.7^{e}
SDF (%/dw)	11.1 ± 1.1^{b}	1.3 ± 0.4^{a}	3.1 ± 0.5^{a}	8.1 ± 1.2^{b}	11.6 ± 1.2^{c}	15.3 ± 1.0^{d}	18.9 ± 0.8^{e}
SDF/TDF	0.25 ± 0.01^{b}	0.41 ± 0.06^{a}	0.38 ± 0.04^{a}	0.17 ± 0.02^{c}	0.20 ± 0.02^{bc}	0.19 ± 0.01^{bc}	0.26 ± 0.03^{b}

Data are expressed as mean ± standard deviation (*n*=3). Values that do not share a lowercase letter within a row differ significantly ($p≤0.05$). TDF: total dietary fiber, IDF: insoluble dietary fiber, SDF: soluble dietary fiber

Effects of supplementation ratio on bioactive compounds and antioxidant capacities of pasta

The levels of bioactive compounds and antioxidant capacities in SPP surpassed those in DWS (Table 2). In particular, SPP showed a 6.0 and 32.8-fold increase in total phenolic and flavonoid levels, respectively, and a 23.4 and 16.5-fold greater antioxidant capacity measured by DPPH and FRAP assays, respectively, compared to DWS. The total phenolic content and antioxidant capacity of SPP were higher than those of some by-products derived from other fruits and vegetables, including orange peel (642 mg/100 g GAE/100 g dw; 2020 - 3576 µmol TE/100 g dw), banana peel (500 mg GAE/100 g dw; 2388 – 4160 µmol TE/100 g dw) [40], and potato peel (950 mg GAE/100 g dw; 13 - 30 µmol TE/100 g dw) [41]. Furthermore, SPP demonstrated a significant content of anthocyanins, whereas DWS lacked detectable levels of these compounds. Previous studies report that anthocyanins serve as potent antioxidants that reduce oxidative stress at both cellular and organismal levels [42,43], making SPP a promising source for health improvement. Therefore, partial replacement of DWS with SPP in pasta formulation would increase bioactive levels, ultimately benefiting consumer health.

The antioxidant contents and capacities of the uncooked pasta increased significantly as the supplementation ratio rose from 0 to 40% (Figure 1). The pasta samples exhibited an enhancement in total phenolic content, with increase of 62, 128, 238, and 456% compared to that of the control at SPP proportion of 10, 20, 30, and 40%, respectively (Figure 1A) due to high phenolic level in SPP. Additionally, the control pasta lacked anthocyanins because they are absent in wheat flour. However, the addition of 40% SPP into to pasta recipe markedly enhanced the flavonoid and anthocyanin contents of the product, reaching 680 mg QE/100 g dw and 49 mg C3GE/100 g dw, respectively (Figure 1B).

Similarly, the increase in SPP level in pasta formulation resulted in an enhancement of antioxidant capacities recorded by DPPH and FRAP assays (Figure 1C). The DPPH and FRAP values of pasta sample incorporated with 40% SPP were found to be 10 and 12 times, respectively, higher than those of the control. An enhancement in antioxidant activity was observed in pasta enriched with dry-dehulling by-products of mung beans [44] and residues of sweet corn milk [45]. At comparable supplementation levels, pasta supplemented with SPP exhibited greater antioxidant activity than that supplemented with sweet corn milk residues; however, it was lower than the antioxidant activity observed in pasta supplemented with mung bean by-products. The presence of phenolics, flavonoids, and anthocyanins was positively correlated with the enhancement in antioxidant capacity of pasta samples supplemented with SPP

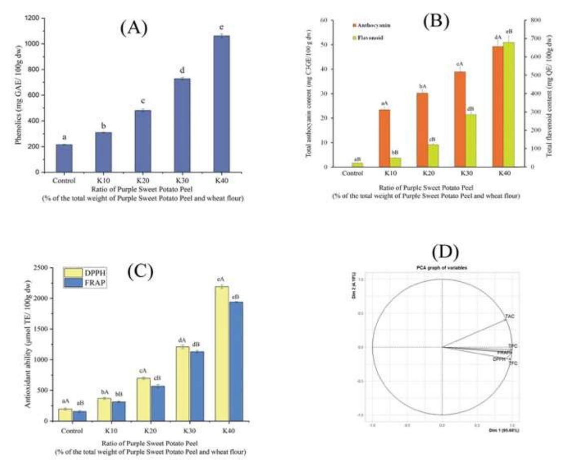

Figure 1. Total phenolic contents (A); Total flavonoid content and total anthocyanin content (B); DPPH free radical scavenging activity and iron reduction ability (FRAP) (C); and correlation of phenolic, flavonoid, anthocyanin, DPPH, and FRAP content vectors of pasta samples with different ratios of SPP (D) K10, K20, K30, and K40: pasta substituted with 10%, 20%, 30%, and 40% SPP,respectively; C3GE: cyanidin 3-O-glucoside equivalent; GAE: gallic acid equivalent; QE: quercetin equivalent; TE: Trolox equivalent; DPPH: 2,2-diphenyl-1-picrylhydrazyl; dw: dry weight.

Values with different lowercase letters in the same legend and uppercase in the same sample are significantly different (p<0.05).

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as evidenced by the vector alignment depicted in Figure 1D. These bioactive compounds markedly increased the antioxidant capacity, boosting the overall antioxidant potential of the product and contributing to the promotion of human health.

Table 2 Antioxidant activity of purple sweet potato peel powder (SPP)\\ and durum wheat semolina (DWS) used for pasta making

Antioxidant Activity	SPP	DWS
Total phenolics (mg GAE/100 g dw)	1825.8 ± 60.2^b	304.3 ± 17.1^a
Total flavonoids (mg QE/100 g dw)	1510.3 ± 67.0^b	46.0 ± 8.9^a
Total anthocyanin content (mg C3GE/100 g dw)	245.5 ± 3.8	ND
Ferric reducing antioxidant power (μmol TE/100 g dw)	3952 ± 85.4^b	169.3 ± 38.6^b
DPPH radical scavenging activity (μmol TE/100 g dw)	4165 ± 70.5^b	252.1 ± 33.9^b

Data are expressed as mean ± standard deviation (*n*=3). Values that do not share a lowercase letter within a row differ significantly ($p≤0.05$). C3GE: cyanidin 3-*O*-glucoside equivalent, GAE: gallic acid equivalent, QE: quercetin equivalent, TE: Trolox equivalent, DPPH: 2,2-diphenyl-1-picrylhydrazyl, dw: dry weight, ND: not determined

Effects of supplementation ratio on cooking and textural properties, instrumental color, and overall acceptability of pasta

Pasta incorporated with 0 to 40% SPP exhibited significant changes in cooking and textural properties, instrumental color, and overall acceptability (Table 3). The cooking quality of pasta demonstrated statistical differences as the substitution ratio increased from 10% to 40% compared to that of the control sample. An increase in the addition level from 0 to 40% resulted in a 59% reduction in optimal cooking time, yet it caused the cooking loss to increase by 2.5 times. Our findings align with the previous research, which reports that an increase in fiber content, particularly soluble fiber, weakens the starch–gluten matrix, consequently leading to enhanced water absorption and a reduced optimal cooking time [46].

WAI reveals how water interacts with the product throughout the cooking process, meanwhile SI measures changes in product volume before and after the cooking [47]. An increase in fiber content in pasta led to a decrease in the SI and WAI by 39 and 37%, respectively. The reduction was attributed to the high hydrophilicity of dietary fiber in the pasta samples, which might prevent the starch granules from absorbing water and swelling [17]. Consequently, this phenomenon reduced the SI and WAI of the fortified pasta.

The elongation rate and tensile strength of pasta samples both exhibited a significant decline with an increasing SPP ratio, indicating diminished extensibility and structural integrity. The control sample demonstrated the highest values for both properties, whereas pasta fortified with 40% SPP exhibited the lowest. These results suggest that the SPP supplementation rendered the pasta less flexible and more susceptible to breakage under various stress conditions. Similarly, the reduced elongation rate and tensile strength of noodles incorporated with pomelo peel may result from a weaker gel network structure, which is caused by increased water content absorption[48].

Table 3 Cooking quality, texture properties, and instrumental color, and overall acceptability of pasta samples supplemented with purple sweet potato peel powder (SPP)

Cooking quality	Control	K10	K20	K30	K40
Optimal cooking time (min)	13.5 ± 0.1^a	8.4 ± 0.1^b	7.3 ± 0.1^c	6.5 ± 0.1^d	5.6 ± 0.2^e
Cooking loss (%)	4.1 ± 0.1^a	5.8 ± 0.3^b	7.3 ± 0.3^c	9.2 ± 0.1^d	10.3 ±0.2^e
Swelling index	2.3 ± 0.1^a	2.1 ± 0.1^b	1.8 ±0.1^c	1.6 ± 0.1^d	1.4 ± 0.0^e
Water absorption index	1.9 ± 0.1^a	1.7 ± 0.1^b	1.5 ± 0.1^c	1.4 ± 0.0^d	1.2 ± 0.0^e
Physical properties					
Hardness (g)	2247.0 ± 15.5^a	2854.2 ± 95.5^b	3461.8 ± 117.6^c	4209.3 ± 45.6^d	5030.2 ± 40.7^e
Cohesiveness	55.3 ± 0.6^a	49.8 ± 1.4^b	47.6 ± 0.1^c	45.2 ± 0.7^d	40.3 ± 0.1^e
Gumminess (g)	1218.5 ± 22.0^a	1393.7 ± 33.8^b	1617.9 ± 70.3^c	1865.0 ± 34.0^d	1989.5 ± 18.7^e
Chewiness (g)	1213.9 ± 22.2^a	1388.5 ± 35.0^b	1612.4 ± 71.8^c	1855.5 ± 33.4^d	1985.4 ± 18.7^e
Elongation rate (%)	42.5 ± 0.7^a	33.1 ± 0.8^b	21.9 ± 0.3^c	14.9 ± 1.4^d	9.9 ± 0.8^e
Tensile strength (kPa)	15.5 ± 0.3^a	12.9 ± 0.7^b	11.6 ± 0.1^c	10.1 ± 0.1^d	7.5 ± 0.6^e
Color values					
L*	85.5 ± 0.2^a	68.3 ± 0.2^b	67.1 ± 0.1^c	65.5 ± 0.1^d	63.3 ± 0.3^e
a*	1.6 ± 0.0^a	5.4 ± 0.3^b	5.9 ± 0.0^c	6.5 ± 0.1^d	7.7 ± 0.1^e
b*	17.0 ± 0.0^a	8.8 ± 0.1^b	7.7 ± 0.2^c	6.2 ± 0.0^d	5.1 ± 0.1^e
ΔE	0^a	19.4 ± 0.4^b	21.1 ± 0.2^c	23.3 ± 0.3^d	25.9 ± 0.4^e
Overall acceptability score	7.2 ± 1.2^a	7.1± 1.0^a	6.3 ± 1.0^b	5.1 ± 1.4^c	4.9 ±1.1^c

Abbreviations: K10, K20, K30, K40, pasta incorporated with 10%, 20%, 30%, and 40% purple sweet potato peel powder, respectively. L*, lightness; a*, greenness (−) to redness (+); b*, blueness (−) to yellowness (+); ΔE, total color difference. Values are means of triplicate ± standard deviation. Values with a different lowercase superscript letter in each row are significantly different ($p < 0.05$)

The hardness of pasta with 40% SPP ratio was 2.2-fold greater than that of the control. The increased hardness of pasta resulting from the addition of fiber entailed modifications to the starch-protein matrix within the pasta. Excessive levels of IDF

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polymerization and crystallization may increase the hardness of high-fiber pasta [49]. Similarly, the gumminess and chewiness of the pasta with 40% SPP were 63% and 64%, respectively, greater than those of the control. In contrast, pasta supplemented with 40% SPP exhibits significant reductions in cohesiveness, tensile strength, and elongation rate, recorded at 27, 52, and 77%, respectively.

As the proportion of SPP supplementation increased, the L* value significantly decreased ($p < 0.05$), resulting in the pasta appearing darker. The pasta with increased SPP levels had a more pronounced purple hue, as indicated by the increased a* value and the decreased b* value [50], in comparison to the control pasta, attributed to the anthocyanins in SPP. Consequently, a more remarkable fortification ratio led to a more significant variation in color of the product.

The control pasta and 10% SPP-fortified pasta had similar overall acceptability scores ($p > 0.05$). However, the overall acceptability of pasta decreased as the SPP proportion rose from 10 to 30%. The supplementation of SPP increased the pasta hardness and consequently decreased its overall acceptability. A negative correlation (r = 0.97) was observed between pasta hardness and sensory scores, indicating that the increased hardness significantly reduced overall acceptability.

Pasta fortified with 10% SPP achieved a desirable balance, qualifying as a high-fiber product while maintaining acceptable cooking quality, color characteristics, and sensory preference. Therefore, a substitution level of 10% SPP was recommended for the development of fiber-enriched pasta products that retain consumer appeal and technological functionality.

Effects of supplementation ratio on predicted glycemic index and antioxidant bioaccessibility of pasta

In vitro digestion simulates the human digestive system across various stages, utilizing digestive enzymes, specific pH values and salt concentrations to evaluate the digestibility of foods as well as the absorption of proteins, carbohydrates, lipids, and bioactive compounds [51]. As the proportion of SPP in the pasta samples increased from 0 to 40%, the GI exhibited a decline of 20%, decreasing from 72.0 to 57.5 (Figure 2). The variation in SPP ratio exhibited notable difference in GI compared to that of the control, which demonstrated a high GI (GI > 70) [52]. The 40% SPP-supplemented pasta was classified as having a low GI (GI < 55). In contrast, the remaining samples with replacement ratio of 10, 20, and 30% SPP, were categorized as possessing a medium GI (55 < GI < 70). The reduction in the GI value was primarily due to the reduced starch content in the product (Table 2). Besides, the increased content of SDF in the fortified pasta samples might enhance viscosity in the small intestine and inhibit glucose uptake across the intestinal wall [53]. Concurrently, IDF acts as a mixed-type inhibitor of α-amylase in the small intestine by van der Waals and/or hydrogen bonding forces, thereby significantly retarding starch digestion by reducing both the digestion rate and digestible starch content [54]. Additionally, Su et al. (2021) demonstrate that four phenolic acids present in purple sweet potato namely 4-hydroxybenzoic acid, ferulic acid, caffeic acid, and isoferulic acid, significantly reduce the digestibility of starch. They could alter the secondary structure of α-amylase and α-glucosidase, interacting with specific amino acid residues in non-catalytic sites via hydrogen bonds to probably perturb the protein structure and inhibit these enzymes in a non-competitive manner [55]. Previous studies also report a GI-lowering effect by the incorporation of watermelon rind [56], and okara [57] in pasta formulas.

Figure 2A demonstrates that the antioxidant bioaccessibility of all fortified pasta samples was significantly greater than that of the control. Notably, the bioaccessibility of phenolics, flavonoids, and anthocyanins increased by 3.3, 2.9, and 2.1-folds, respectively, as the level of SPP in pasta formulation was

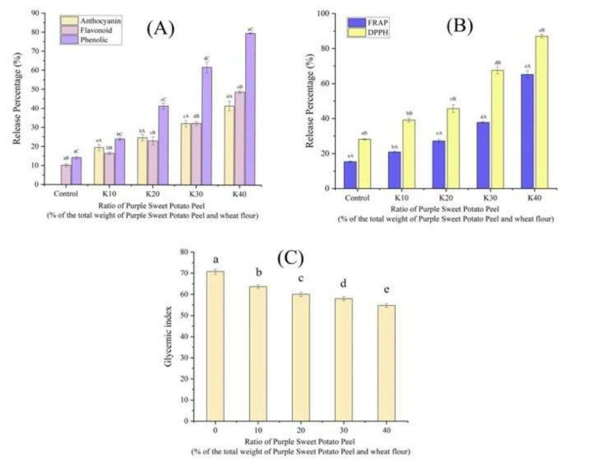

Figure 2. Release of phenolics, anthocyanins, and flavonoids (A), Release of antioxidant activities (B), and predicted GI (C) of pasta samples with different ratios of purple sweet potato peel powder.

Abbreviations: K10, K20, K30, K40, pasta incorporated with 10%, 20%, 30%, and 40% purple sweet potato peel powder, respectively. DPPH: 2,2-diphenyl-1-picrylhydrazyl, dw: dry weight. Values with different lowercase letters in the same legend and uppercase in the same sample are significantly different ($p<0.05$).

enhanced from 10 to 40%. Different pH values and digestive enzymes of the stomach and intestine jointly influence the release of phenolic compounds at the stomach and intestine phases of the digestion. At the gastric phase, the low pH environment creates favourable conditions for releasing phenolic compounds [58]. During the intestinal phase, pancreatin facilitates the disruption of peptide bonds in phenolics-protein complexes and glycosidic bonds in phenolics–fiber complexes, thereby weakening non-covalent interactions (such as hydrogen bonds, hydrophobic interactions, and ionic bonds) between phenolics and these macromolecules, and liberating them from the matrix [59,60]

Anthocyanins and phenolic acids exhibit antioxidant and anti-inflammatory effects but the gastrointestinal digestion conditions likely impact their bioaccessibility [61]. Therefore, the high bioaccessibility of these compounds within the

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gastrointestinal tract could be advantageous for evaluating their overall bioavailability and the potential health benefits. In our study, a positive correlation was recorded between the SPP levels in the pasta formulation and the bioaccessibility of phenolics (r=0.99), flavonoids (r=0.97), and anthocyanins (r=0.97). Rocchetti et al. (2021) propose that the increased dietary fiber supplementation has a significant carrier effect on anthocyanins in the small intestine through interactions between fiber and anthocyanins, thereby enhancing their bioaccessibility [62].

The proportion of antioxidant activity of the cooked pasta samples released at the intestinal phase and that at the beginning of the *in vitro* digestion is illustrated in Figure 2B. The proportion of antioxidant activities evaluated by both DPPH and FRAP assays showed a significant increase due to the SPP supplementation. This enhancement was likely related to the amount of phenolics, flavonoids, and anthocyanins released from the digested pasta. Pasa with 40% SPP replacement had the highest proportion of antioxidant activity.

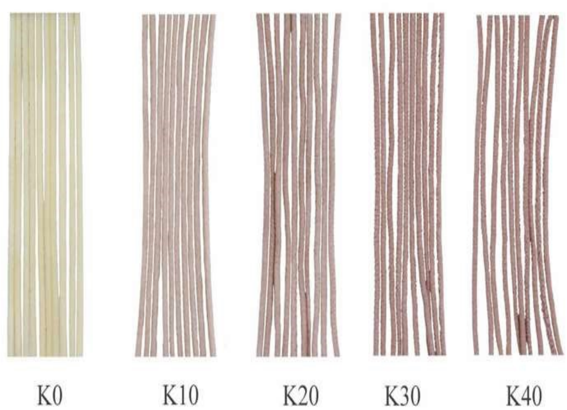

Figure 3. Appearance of pasta from wheat flour (K0) and pasta from blends of wheat flour with different proportions (K10-K40)

Abbreviations: K10, K20, K30, K40, pasta incorporated with 10%, 20%, 30%, and 40% purple sweet potato peel powder, respectively.

Conclusions

The innovation of this study resides in the integration of health benefits with sustainability by utilizing purple sweet potato peel—an accessible agro-industrial by-product—as a functional ingredient in pasta. This approach increases dietary fiber and antioxidant intake while exemplifying principles of the circular bioeconomy and waste-to-value strategies. This represents a novel product concept that combines nutritional, environmental, and economic advantages. This research revealed the potential of using SPP as a novel ingredient in the making of high-fiber pasta. Compared to the control, pasta samples supplemented with 10 to 40% SPP exhibited a significant increase in dietary fiber, phenolic, flavonoid, and anthocyanin contents, as well as antioxidant capacities. Moreover, the SPP supplementation led to a decrease in glycemic index (GI), rendering SPP-enriched pasta products suitable for the preventing elevated blood sugar levels. The antioxidant bioaccessibility and antioxidant capacity of cooked pasta increased with the SPP addition level. Pasta samples fortified with 40% SPP showed a 3.3-fold increase in the bioaccessibility of phenolics, a 2.9-fold increase in that of flavonoids, and a 2.1-fold increase in that of anthocyanins compared to the control. Additionally, the antioxidant activities of the 40% SPP-added pasta in the intestinal phase, evaluated by DPPH and FRAP assays, increased by 3.1 and 4.2-fold, respectively, compared to those of the control. Although the increased SPP level led to an enhanced hardness and cooking loss, and a declined sensory acceptability, SPP could serve as a valuable ingredient in the making of functional pasta with a reduced GI and improved antioxidant bioaccessibility. Future research should focus on kneading conditions to enhance the texture and consumer acceptance of high-fiber pasta. Additionally, cell-based or in vivo studies are needed to confirm the glycemic-lowering and antioxidant effects.

Author contributions

Thanh Tung Bui conducted the experimental work, performed statistical analysis, and wrote the manuscript. Van Viet Man Le supervised the project, contributed to manuscript writing, and provided conceptual guidance. Van Nguyen Tran offered research advice, helped consolidate data, and contributed to manuscript writing. All authors participated in the article review process.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The article includes the data that were utilized for the study.

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Data availability

The article includes the data that were utilized for the study.