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Research article

UTILIZATION OF POMELO FLAVEDO WASTE FOR DEVELOPMENT OF BIOACTIVE ENRICHED PASTA: PHYSICOCHEMICAL, FUNCTIONAL, TEXTURAL AND SENSORIAL CHARACTERISTICS

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ABSTRACT

Pomelo flavedo is appreciated for its high dietary fiber content and is composed of many health-beneficial phytochemicals during processing. The present study aimed to maximize the potential of incorporating pomelo flavedo powder as a bioactive ingredient in pasta. The results showed that the incorporation of pomelo flavedo at five different concentrations (0, 3, 6, 9, and 12%) in pasta preparation had a great influence on its antioxidant, functional, textural, and sensorial properties. The addition of flavedo powder markedly increased the antioxidant properties and significantly increased the WAC (121.23 to 162.36%) and OAC (110.15 to 124.43%). An increase in pomelo flavedo is associated with a decrease in cooking time from 10.24 to 8.32 min, with cooking loss within an acceptable range. The pomelo flavedo concentration significantly improved the sensorial profile and reduced the breaking stress, fracturability, firmness and hardness of dry pasta but increased the adhesiveness and cohesiveness of wet pasta. FTIR analysis of the cooked pasta indicated that the presence of fibers in the flavedo revealed the presence of characteristic peaks. SEM revealed that the microstructure of the pomelo flavedo affected the structural integrity of the pasta. Among the different pomelo flavedo formulations tested, pasta with 6% pomelo flavedo obtained an acceptability score of 7.95%. Thus, pomelo flavedo can be incorporated into the industry for the preparation of pasta and is considered a healthy choice for people with specific nutritional requirements.

1. Introduction

There is an increasing demand for healthier food and products with an increase in the population and a change in lifestyle. Consumers' preferences divert toward food composed of bioactive compounds such as dietary fibers, polyphenols, and vitamins that may have health benefits (Sharma et al., 2024). The fruits and vegetable byproducts generated from the processing of raw fruits and vegetables are excellent sources of phytoconstituents, polyphenolic compounds, flavonoids, phenolics and nutrients. These byproducts are obtained as functional ingredients for food products and provide economic and health benefits (Deb et al., 2025).

Pomelo, scientifically known as *Citrus grandis,* belongs to the family *Rutaceae* and is one of the largest fruits among citrus varieties. Pomelo fruit generates a large amount of waste, including peel, pomace, and seeds, which are composed of bioactive compounds. The bioactive compounds carried in waste improve health benefits (Tocmo et al., 2020). Pomelo peel is considered the largest and thickest rind among all citrus fruits and comprises up to 40% of the fresh weight of the fruit. Pomelo fruit peel is composed of two layers: the flavedo outer layer consists of a cuticle and is covered by a thin epidermal layer, and the albedo inner layer consists of white, spongy tissue (Gamonpilas et al., 2021). The peels can improve lipid metabolism and include high levels of phytochemicals such as dietary fiber (DF), flavonoids, polyphenols, and betalain (Nasehi, 2020). The flavedo of pomelo fruits is an enriched source of bioactive constituents with health-promoting benefits and provides a significant source of fiber (Saini et al., 2022). Dietary fibers are the foremost important component of pomelo fruit, as the presence of fibers in the body improves its metabolism and digestion. Consuming fibers may bring health benefits such as a lower risk of cancer and metabolic syndrome (Babaoğlu et al. 2022). There is an increasing trend in the market for value-added products with high levels of nutritional and active compounds (Gamonpilas et al., 2021; Xiao et al., 2021). Pomelo flavedo is considered a high-value component because it consists of a large number of phytochemicals and has multiple uses in the food industry. Numerous value-added components and a wide range of valued prospects exist in the provinces that improve health and technology from the waste produced by pomelo flavedo. Pomelo flavedo's bioactive chemicals and health advantages are widely known among customers due to the creation of new culinary products from waste (Angulo-López et al. 2022). The consumption of these components is enhanced by incorporating them into popular foods such as pasta or bread (Xiao et al., 2021). Crizel et al. (2015) stated the bioactive impact of orange byproduct based pasta and results reported that the incorporation of byproduct fiber improved the functional and technological properties of pasta. The study reported by Gumul et al. (2023) demonstrated the functional and health-promoting impact of apple pomace incorporated pasta. Likewise, Gałkowska et al. (2022) evaluated the health advantages related to bioactive potential and antioxidant activity of blackcurrant pomace fortified pasta.

Pasta is one of the most consumed foods worldwide and has low fat, cholesterol, and high carbohydrate contents. It is a popular *Italian* product with different pasta brands the commonly consumed are spaghetti, penne, lasagna, ravioli, linguine, rigatoni, farfalle, fusilli, macaroni, cannelloni (Panza et al., 2023). Pasta is made from durum wheat semolina to provide protein and carbohydrates, but incorporating components such as dietary fibers is an excellent approach for increasing nutritional value, which could lead to functional products (Gamonpilas et al., 2021). Pomelo flavedo with its valuable properties showed the potential to make shelf-stable, healthy and high-quality pasta (Baigts-Allende et al., 2023). The scope of the above facts is considered in the present study to formulate the flavedo powder incorporated pomelo pasta and to explore the proximate, antioxidant, functional, cooking, textural, structural and sensorial attributes of the formulated product.

2. Materials and methods

2.1. Materials

Pomelo fruits were procured from the Department of Fruit Science, Punjab Agricultural University, Ludhiana, India for the year 2024. The selected fruits were washed, cleaned and separated into different components, from which flavedo was further taken into consideration for pasta preparation. The pomelo flavedo was freeze-dried at -70 °C and 0.0500 mbar using a CHRIST-Alpha 2-4 LSC-basic lyophilizer. Freeze-dried pomelo flavedo was powdered using a grinder and vacuum-stored in polythene bags for further analysis. Durum semolina, xanthan gum and salt were purchased from a local market.

2.2. Pasta preparation

Pasta was prepared by using a screw extruder machine (Doly La Monferrina, Italy) with different pomelo flavedo concentrations (0, 3, 6, 9 and 12 g). The semolina (97, 94, 91, 88 and 85 g), xanthan gum and salt raw materials with an appropriate amount of water were slowly added, mixed and kneaded until a homogenous dough was obtained. The dough was extruded with an adjustable die of the desired shape and cut to a length of 3 cm and a width of 1.5 cm using a cutter attached to the extruder. The formulations used for the production of pomelo flavedo-enriched pasta are detailed in Table 1. Pasta was dried at 50 °C for 5 h in hot air oven (Meta-Lab Scientific Industries Mumbai, India), cooled to room temperature, packed and stored in polyethylene bags for further analysis.

Table 1. Composition of the mixture used to prepare pomelo flavedo-incorporated pasta

Sample name	Semolina (g)	Pomelo flavedo powder (g)	Xanthan gum (g)	Salt (g)
Control	97	0	2	1
PFP3	94	3	2	1
PFP6	91	6	2	1
PFP9	88	9	2	1
PFP12	85	12	2	1

C: Control**; PFP3:** pomelo flavedo pasta 3%; **PFP6:** pomelo flavedo pasta 6%; **PFP9:** pomelo flavedo pasta 9%**; PFP12:** pomelo flavedo pasta 12%

2.3. Proximate composition of flavedo powder and pasta samples

The moisture content (method 930.04), total ash content (method 930.05), crude fat (method 930.09), crude fiber (method 978.10) and crude protein (method 978.04) of pasta samples were estimated using standard methods (AOAC, 2000). Carbohydrates were determined by a difference method, and the sum percentage of moisture, ash, fat, crude fiber and protein was subtracted from 100 and estimated according to the AOAC (2005) standard procedure.

$$Antioxidant\ activity\ (\%) = \frac{Abs(control) - Abs(sample)}{Abs(control)} \times 100 \quad (1)$$

Abs (control) = Absorbance of control

Abs (sample) = Absorbance of experimental sample

2.4. Antioxidant properties of pasta

Antioxidant activities in the form of DPPH (2,2-diphenyl-1-picrylhydrazyl) and FRAP (ferric reducing antioxidant power) radical scavenging activities of uncooked pasta were determined by Córdoba-Cerón et al. (2023). The total phenolic and total flavonoid contents were estimated by Folin-Ciocalteu photometric and aluminum chloride methods as proposed by Oyeyinka et al. (2021). Antioxidant activity was calculated using the following equation:

2.5. Functional properties of pasta

The functional properties, including water and oil absorption capacity, were estimated in uncooked pasta (Córdoba-Cerón et al., 2023). Samples (2 g) were added to 10 ml of water or vegetable oil in pre-weighed 50 ml centrifuge tubes and incubated for 30 min. The mixture was centrifuged (Tabletop centrifuge, Thermo Fisher Scientific, U.S.) at 1693×g for 15 min, and the supernatant was collected. The WAC/OAC of pasta was calculated by the following formula:

$$WAC\ (\%) = \frac{Weight\ of\ dry\ solids\ after\ removal\ of\ supernatent\ (g) - Weight\ of\ sample\ (g)}{Weight\ of\ sample\ (g)} \times 100$$
$$OAC\ (\%) = \frac{Weight\ of\ dry\ solids\ after\ removal\ of\ supernatent\ (g) - Weight\ of\ sample\ (g)}{Weight\ of\ sample\ (g)} \times 100$$
(2)

WAC = Water absorption capacity
OAC = Oil absorption capacity

2.6. Cooking quality of pasta

The cooking characteristics, including cooking time, cooking loss, cooking weight, volume expansion, and swelling index, were identified for each sample of cooked pasta by the method given by Krawęcka et al. (2020). For cooking time, the 10 g sample was combined with 100 ml of deionized water, and the mixture was cooked The pasta was taken out of the oven after 30 seconds and examined for the removal of the white core by pressing it between the glass plates. The ideal cooking time (OCT) is defined as the amount of time (in minutes) needed for the center white core to completely vanish. The weight of 10 grams of dry pasta after cooking was used to calculate the cooked weight (CW). Volume expansion was evaluated by using a 250 ml measuring cylinder containing a 10 g sample filled with 200 ml of pure water. The volume was determined by recording the rise in volume and measured in ml/g. Cooking loss (CL) was determined using a petri plate that had been previously weighed and was filled with 10 ml of the aliquot, which was then left to dry at 105 °C. Swelling index was determined by pre-weighing 50 ml centrifuge tubes were filled with 0.5 g of the sample and 15 ml of deionized water. The sample was cooled and heated to 85 °C for 30 minutes and centrifuged for 15 minutes at 1693 ×g using a Sorvall ST 16R centrifugation (Thermo Fisher Scientific, Germany). The weight of sediments recorded and supernatant discard of and calculated by the following formula:

$$SP = \frac{Weight\ of\ swollen\ sediments\ (g)}{Weight\ of\ sample\ (g)}$$
(3)

2.7. Color

The color (L*, a* and b*) of uncooked pasta was measured using the Hunter Lab Color Flex (Hunter Associates Inc., USA) as described by Oyeyinka et al. (2021). The average value of three measurements was reported for L*, a* and b* values, where L* indicates whiteness/darkness, a* represents redness/greenness (+ a = redness, - a = greenness), and b* represents yellowness/blueness (+ b = yellowness, - b = blueness).

2.8. Textural attributes of pasta

The textural components, including the breaking stress, fracturability and stiffness, were evaluated on dry pasta, and the firmness and work of cutting were determined on wet pasta samples as described by Chauhan et al. (2017). The textural properties, including hardness, adhesiveness, springiness, cohesiveness, chewiness and resilience, of the cooked pasta were illustrated using a texture profile analyzer (TPA) (TA-HD plus, Stable Micro Systeme, UK) as described by Ungureanu-Iuga et al. (2020).

2.9. Structural and morphological characteristics

The functional groups in the developed pasta were studied using Fourier transform infrared (FTIR) spectroscopy (PerkinElmer, USA) according to the method mentioned by Zhao et al. (2024). The microstructure of the uncooked pasta samples was identified using scanning electron microscopy (SEM) (Model: Hitachi S 3400 N, UK) following the method suggested by Ahmed et al. (2024).

2.10. Sensory analysis

The sensory analysis of cooked pasta was conducted at the Department of Food Science and Technology, PTU, Jalandhar, India, by a panel of 30 members. The samples were evaluated for their appearance, texture, aroma, taste, and overall acceptability on a 9-point hedonic scale, which ranges from extremely liked (9) to extremely disliked (1).

2.11. Statistical analysis

All analysis was performed in triplicate, and the final values are reported as the mean ± standard deviation (SD). Data for different treatments were analyzed using one-way analysis of variance (ANOVA) with IBM SPSS Statistics version 22 software (Armonk, NY: IBM Corp.), and Tukey's post hoc test ($p = 0.05$ or $p < 0.05$) was used to compare groups.

3. Results and discussion

3.1. Proximate composition of flavedo powder and pasta samples

The proximate compositions of the flavedo powder and pasta samples were evaluated for different parameters (Table 2). The findings indicated that pomelo flavedo supplementation significantly ($p<0.05$) improved the nutritional profile of the pasta samples. With an increase in flavedo concentration from 0 to 12%, there was an increase in moisture content (6.35±0.03 to 7.19±0.03%), ash content (0.65±0.03 to 1.18±0.03%) and crude fiber (8.46±0.03 to 9.55±0.04%), and a decrease in crude fat (2.08±0.03 to 1.50±0.02%), crude protein (4.68±0.03 to 3.89±0.03%) and carbohydrate content (77.76±0.10 to 76.91±0.03%). According to the standards, the moisture and ash contents should be less than 12-13%, and supplemented pasta samples should be in this range. The results depicted that with the addition of pomelo flavedo, the ash and fiber contents of the final product significantly improved.

Table 2. Proximate composition of pomelo flavedo powder and pasta samples

Pomelo pasta concentrations (%)	**Proximate composition**					
	Moisture content (%)	**Total ash (%)**	**Crude fat (%)**	**Crude fiber (%)**	**Crude protein (%)**	**Carbohydrate (%)**
Pomelo flavedo powder	12.89±0.03^{a}	2.24±0.02^{a}	4.71±0.03^{a}	16.45±0.07^{a}	6.43±0.02^{a}	73.73±0.05^{d}
Control	11.35±0.03^{f}	0.65±0.03^{f}	2.08±0.03^{b}	1.87±0.01^{e}	4.68±0.03^{b}	81.23±0.07^{b}
PFP3	11.75±0.02^{e}	0.91±0.02^{e}	1.91±0.04^{c}	2.72±0.04^{d}	4.52±0.04^{c}	80.92±0.04^{b}
PFP6	11.94±0.02^{d}	1.19±0.03^{d}	1.78±0.03^{d}	4.84±0.05^{c}	4.44±0.04^{c}	80.65±0.06^{c}
PFP9	12.10±0.02^{c}	1.41±0.03^{c}	1.56±0.03^{e}	5.46±0.04^{b}	4.27±0.03^{d}	80.66±0.07^{a}
PFP12	12.29±0.03^{b}	1.63±0.03^{b}	1.50±0.02^{f}	6.55±0.04^{b}	3.89±0.03^{e}	80.70±0.05^{a}

Results are expressed as the mean ± SD (n=3). Values in the same column with different superscripts are significantly different ($p < 0.05$).PFP: pomelo flavedo pasta

3.2. Antioxidant properties of pasta

The antioxidant properties including DPPH, FRAP, TPC and TFC of different formulations (0, 3, 6, 9 and 12%) incorporated pasta were highlighted in Table 3. An increase in the concentration of pomelo flavedo powder significantly improved the antioxidant properties, such as DPPH (17.24±0.05 to 61.24±0.05%), FRAP (7.52±0.02 to 17.47±0.02 µmol AAE/g), TPC (71.50±0.07 to 87.96±0.06 mg GAE/g) and TFC (77.80±0.21 to 226.18±0.15 mg CE/g), of the fortified pasta samples. The incorporation of pomelo flavedo powder doubled the antioxidant potential of the product due to the high content of bioactive compounds such as flavonoids, phenolics, vitamins and polyphenols present in the flavedo. Pomelo flavedo waste is an enriched source of fibers and has the potential to enhance the bioactive and antioxidant profile of the product. Enriching pasta with fruit fiber considerably increases its antioxidant activity, owing to the high polyphenol content of fruits and their byproducts, such as peel. According to studies, adding fruit fiber, such as flavedo peel, increases overall phenolic content and antioxidant capacity (DPPH and FRAP) in pasta. Similar, results are demonstrated by Crizel et al. (2015) for orange by-product fiber incorporated pasta for improving the antioxidant properties. Likewise, results have been reported by Linares-García et al. (2019) for pasta prepared from quinoa with lupine flour and by Wahanik et al. (2018) for turmeric fortified wheat flour pasta.

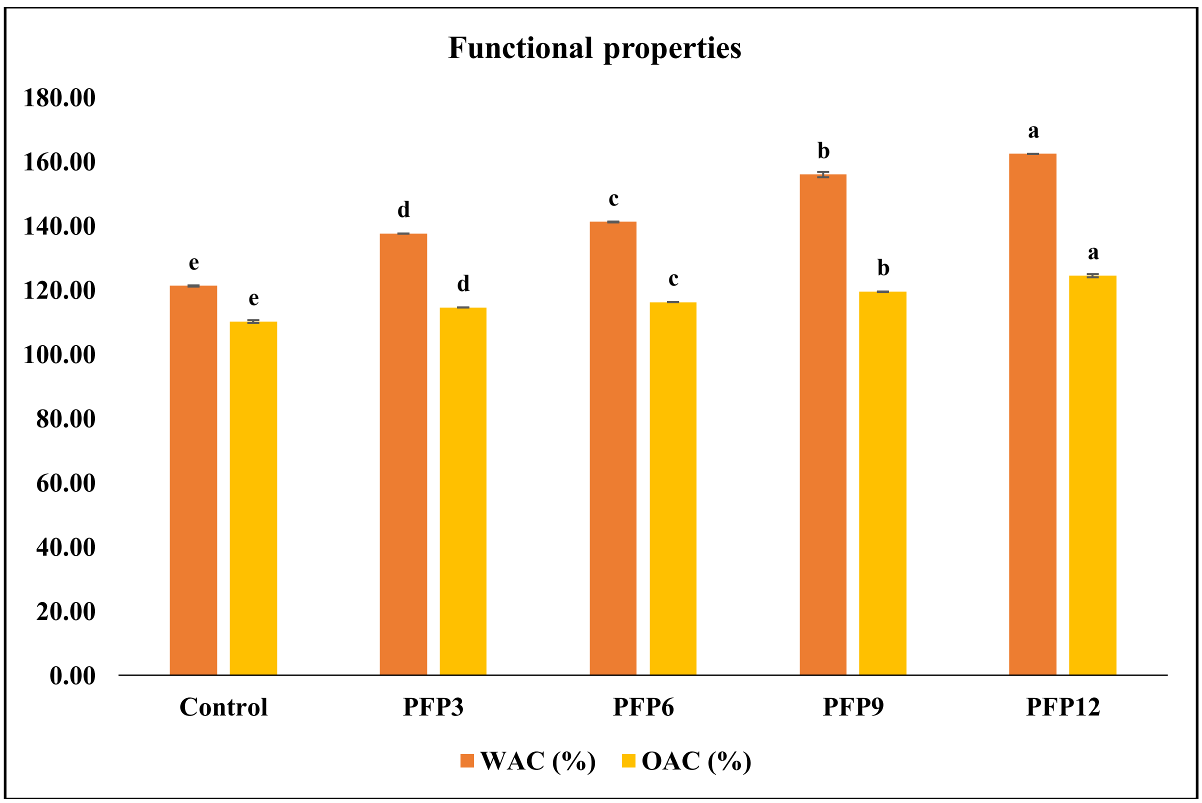


Figure 1. Functional properties of pasta samples with different pomelo flavedo levels (0, 3, 6, 9, and 12%)

3.3. Functional properties of pasta

The water absorption capacity is related to the sum of water bound by the product, and the oil absorption capacity reflects the ability of the product to absorb oil, which determines the texture and mouth feel of the products. A significant increase in the WAC from 121.23±0.20 to 162.32±0.02% and in the OAC from 110.15±0.44 to 124.43±0.49% was observed with increasing flavedo powder concentration, as shown in Figure 1. The pomelo flavedo-incorporated pasta showed an increase in the WAC and OAC due to the strong water affinity of the fibers. An increase in the fiber content of pomelo flavedo is responsible for weakening the gluten network, enabling water penetration, and increasing water and oil absorption. The weakening of the gluten network causes the disintegration of solids and is indicated in water absorption, volume increase, and loss in cooking parameters. Similarly, results have been reported by Crizel et al. (2015) for pasta comprising fibers extracted from orange byproducts.

3.4. Cooking quality of pasta

Cooking properties such as cooking time, cooking loss, cooking weight, volume expansion and swelling index are used to assess the overall quality of pasta. Good-quality pasta should be in good shape, increase in weight and cause less gruel loss, thus preserving the aesthetic value of the product. A significant decrease in cooking time was observed from 10.24±0.03 to 8.32±0.04 min as the pomelo flavedo content increased from 0 to 12% (Table 3). The declining trend in cooking time was due to the pasta center absorbing more water because of the weak gluten-starch network. Additionally, due to an increase in fiber content, fibrous food takes more time for water to imbibe during the cooking process. These results are in accordance with the findings of Ciccoritti et al. (2019) for bran-enriched pasta. Another important parameter for identifying the quality of pasta is cooking loss. Cooking loss indicates the release of solids from pasta into cooking water. The cooking loss of pasta is influenced by fiber addition; as uniform diffusion of cooking water is related to the potential of the starch protein matrix to preserve its physical integrity during the cooking process. The cooking loss of pasta increased from 3.89±0.04 to 5.26±0.07% as the pomelo flavedo powder content increased from 0 to 12%. The increase in cooking loss reflects the disruption of the protein starch matrix with uneven water distribution within the pasta matrix due to the tendency of fibers to be hydrated and the weakening of the gluten network by the fibers. Similarly, cooking loss was illustrated by Espinosa-Solis et al. (2019) in oat bran and apple flour-based pasta.

Cooking weight is associated with the amount of water absorbed by the pasta during the cooking process. The addition of fiber slowly reduced the cooking weight from 12.48±0.07 to 10.62±0.07 g because of the low retention of water and weakening of the gluten network. Gluten is diluted with fibers and starch, reflecting a decrease in the amount of water held in the materials and increased cooking losses, thus reducing the cooking weight. The volume expansion and swelling indices increased with increasing pomelo flavedo content from 0 to 12%. The volume expansion of the cooked pasta increased from 5.37±0.05 to 6.78±0.03 ml/g, and the swelling index increased from 6.54±0.08 to 7.32±0.05%. This might be due to the increased water absorption capacity, which reflects greater volume expansion and a greater swelling index. These results are consistent with the findings of Surasani et al. (2019), who reported that pasta supplemented with protein isolated from pangas waste exhibited greater volume expansion. Similarly, an increase in the swelling index was reported by Ungureanu-Iuga et al. (2020) for pasta prepared from grape peel and whey powder.

3.5. Color profile

One of the significant parameters that describes pasta quality is color. Color is expressed as L*, a*, and b* values, which have a very strong effect on the final choices of consumers. The incorporation of different ingredients could strongly alter the color of the pasta formulation. With an increase in pomelo flavedo from 0 to 12%, there was a decrease in brightness (L*) (73.33±0.97 to 55.26±1.43) and an increase in greenness (a*) (1.93±0.32 to 5.21±0.23) and yellowness (b*) (13.44±0.47 to 23.78±2.27) (Table 4). The addition of ingredients modifies the color of pasta formulations. The increase in a* = greenness and b* = yellowness values of pasta was due to the high levels of naturally occurring carotenoids such as β-carotene and zeaxanthin. The decline in L* values reveals the maximum darkness in the 12% formulation caused by an increase in a* = greenness and b* = yellowness, which reduced the overall lightness of the product. Similarly, a reduction in L* values and an increase in b* and a* values were observed in pennywort pomace and tyrosinase fiber-rich pasta (NP et al., 2023) and cashew apple pomace powder-enriched pasta (Nguyen et al., 2023)

Table 3. Antioxidant properties and cooking quality of different formulations of pomelo flavedo incorporated pasta

Pomelo pasta concentrations (%)	Antioxidant properties				Cooking quality				
	DPPH (%)	FRAP (µmol TE/100 g)	TPC (mg GAE/100 g)	TFC (mg CE/100 g)	Cooking time (min)	Cooking loss (%)	Cooking weight (g/10 g)	Volume expansion (ml/g)	Swelling index (g/g)
Control	17.24±0.05^{e}	7.52±0.02^{e}	77.80±0.21^{e}	71.50±0.07^{e}	10.24±0.03^{a}	3.89±0.04^{e}	12.48±0.07^{a}	5.37±0.05^{e}	6.54±0.08^{d}
PFP3	28.52±0.04^{d}	10.57±0.07^{d}	123.86±0.05^{d}	82.84±0.56^{d}	10.21±0.08^{a}	4.26±0.06^{d}	11.81±0.05^{b}	5.75±0.07^{d}	6.62±0.09^{d}
PFP6	38.28±0.86^{c}	12.55±0.03^{c}	177.51±0.21^{c}	85.57±0.01^{c}	9.71±0.05^{b}	4.74±0.09^{c}	11.38±0.07^{c}	6.15±0.03^{c}	6.87±0.04^{c}
PFP9	46.63±0.58^{b}	14.05±0.07^{b}	200.78±0.06^{b}	97.08±0.61^{b}	8.64±0.07^{c}	5.07±0.04^{b}	11.13±0.06^{d}	6.32±0.04^{b}	7.16±0.05^{b}
PFP12	61.24±0.05^{a}	17.47±0.02^{a}	226.18±0.15^{a}	114.63±0.53^{a}	8.32±0.04^{d}	5.26±0.07^{a}	10.62±0.07^{e}	6.78±0.03^{a}	7.32±0.05^{a}

Results are expressed as the mean ± SD (n=3). Values in the same column with different superscripts are significantly different ($p < 0.05$).
PFP: pomelo flavedo pasta; DPPH: 2,2-diphenyl-1-picrylhydrazyl; FRAP: ferric reducing antioxidant power; TPC: total phenolic content; TFC: total flavonoid content; AAE: ascorbic acid equivalent; CE: catechin equivalent

Table 4. Color of different formulations of pomelo flavedo incorporated pasta

Pomelo pasta concentrations (%)	Color		
	L*	a*	b*
Control	73.33±0.97^{a}	1.93±0.32^{e}	13.44±0.47^{d}
PFP3	66.38±1.99^{b}	3.61±0.16^{d}	21.51±0.02^{cb}
PFP6	63.13±0.06^{cd}	4.01±0.33^{c}	22.86±0.15^{b}
PFP9	61.92±2.09^{d}	4.40±0.57^{b}	23.34±2.71^{a}
PFP12	55.26±1.43^{e}	5.21±0.23^{a}	23.78±2.27^{a}

Results are expressed as the mean ± SD (n=3). Values in the same column with different superscripts are significantly different ($p < 0.05$).PFP: pomelo flavedo pasta; L* = brightness; a* = redness; b* = yellowness

3.6. Textural attributes of pasta

Textural properties, including the breaking stress, fracturability, stiffness, firmness, and toughness, revealed a decreasing trend with increasing fiber content (Table 5). The results revealed that the breaking stress decreased from 6.29±0.12 to 3.48±0.17 N/mm^2 with increasing pomelo flavedo powder. The breaking stress of dried pasta is affected by the gluten network. The addition of pomelo flavedo influences its textural properties due to the disruption of the gluten network. Also, the breaking stress of pasta is correlated with sensory traits like firmness and chewiness. Higher breaking stress is related to observed firmness and needed more force to chew. The pasta with 3% incorporation had more breaking stress as compared to other formulations. Pasta fracturability is related to how easily it breaks and stiffness describes that pasta should be firm but not toohard. A decreasing trend was observed for the fracturability and stiffness of the dried pasta. The fracturability varied from 7.35±0.21 to 5.69±0.04 mm, and the stiffness varied from 47.64±0.42 to 28.63±0.55 N/mm^2/sec with increasing pomelo flavedo. Stiffness and fracturability are two important pasta textural characteristics that greatly affect sensory perception and the assessment of overall quality; pasta that is firmer and less fracturable is typically acceptable by the consumer. The pasta with 3% incorporation had more fracturability and stiffness as compared to other formulations. An increment in the fiber levels reflects softening of pasta and thus decreases the fracturability and stiffness of the product. Similarly, findings were reported by Rodriguez-Huezo et al. (2022) for fiber-based pasta. The firmness and toughness of the control and flavedo pasta were studied in cooked pasta. The firmness of the cooked pasta significantly decreased from 678.82±0.29 to 386.35±0.44 g as the pomelo flavedo content increased from that of the control to 12%. Firmness is related to the bond strength and integrity of the protein-fiber matrix present in the cooked pasta and is also a good indicator of consumer acceptance of the product. With increasing fiber concentration, the firmness as the fibers leached out of the starch granules and softened the tissues. Another textural property is toughness is related to the sum of the energy a material can absorb per unit volume before rupturing. The toughness decreased from 584.27±0.55 to 343.88±0.62 g/sec with increment in levels of flavedo powder. This is because an increment in the flavedo powder addition causes the disintegration of the gluten network development. Similar, results for firmness and toughness were obtained by Biernacka et al. (2017) for wheat pasta incorporated with carob fiber.

Textural profile analysis was used to evaluate the hardness, adhesiveness, springiness, cohesiveness, chewiness, and resilience using a texture analyzer (Table 5). For consumer acceptance, pasta with high hardness, springiness, and chewiness is desirable. The hardness of the flavedo powder-formulated pasta ranged from 84.51±0.31 to 56.98±0.82 N. The maximum hardness was achieved for the control pasta, and the minimum hardness was observed for the pasta with 12% pomelo flavedo powder. Pomelo flavedo increment in the formulation decreased the hardness of the pasta, which was due to the increase in fiber content. The incorporation of xanthan gum was utilized to improve texture or to stabilize the gluten network of pasta. The rise in fiber content promoted the development of fractures inside the pasta structure and weakened pasta, which resulted in reduced hardness values. Similarly, outcomes were reported by Martín-Esparza et al. (2018) for pasta prepared from fiber-enriched tiger nut and xanthan gum. The adhesiveness and cohesiveness were directly associated with fiber concentration, with higher fiber levels resulting in higher adhesiveness and cohesiveness values (Espinosa-Solis et al. 2019). The other textural parameters, including springiness, chewiness, and resilience are important textural characteristics in pasta sensory analysis, with springiness indicating the ability to return to its original shape after deformation, chewiness representing the energy required to masticate, and resilience reflecting the pasta's ability to recover afterdeformation. Springiness, chewiness and resilience, of the formulated pasta ranged from 0.92±0.10 to 0.68±0.04, 47.35±4.56 to 25.95±2.08 g/cm and 0.55±0.01 to 0.32±0.03, respectively. The 3% flavedo incorporated pasta had higher values as compared to other formulations. These parameters are directly related to sensory analysis as they significantly influence the perceived mouthfeel and overall quality of food, impacting consumer acceptance and preferences. Similar to the hardness, these parameters decreased with increasing pomelo flavedo powder in the product, and the maximum values were observed for the control pasta.

The results of textural attributes of pasta significantly varied at $p<0.05$ with respect to variations in pomelo flavedo powder concentrations. Thefindings related to a decrease in springiness, chewiness and resilience with an increase in fiber content are reported by Rodriguez-Huezo et al. (2022) and Espinosa-Solis et al. (2019), who prepared fiber-rich pasta.

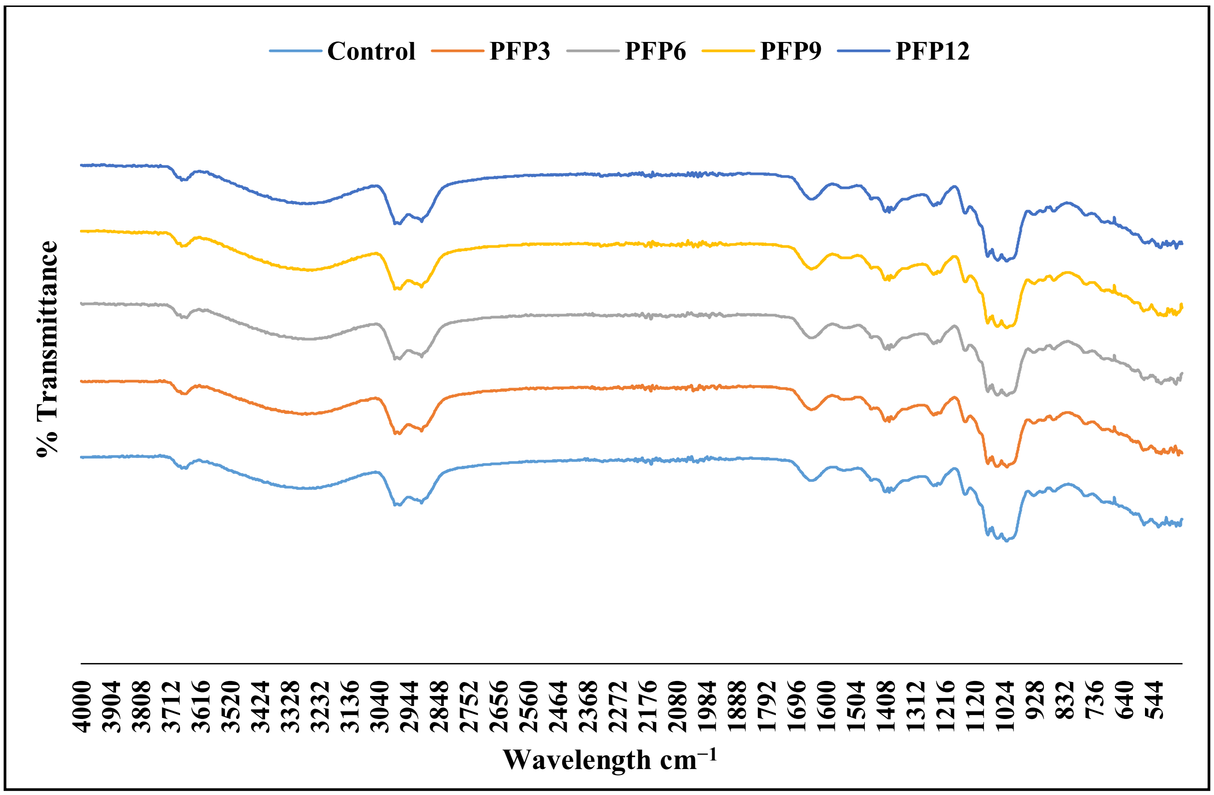


Figure 2. FTIR spectrum of pomelo flavedo-based pasta
C: Control**; PFP3:** pomelo flavedo pasta 3%; **PFP6:** pomelo flavedo pasta 6%; **PFP9:** pomelo flavedo pasta 9%**; PFP12:** pomelo flavedo pasta 12%

3.7. Structural and morphological characteristics

FTIR analysis of the flavedo-incorporated pasta was performed to evaluate the changes in the structure by using the vibrational patterns of various functional groups and the bonding of the different pasta samples, as shown in Figure 2. The O-H stretching band at 3675 cm^{-1} was attributed to the presence of phenolic compounds. The stretching of C-H bonding reflects the vibrations of lipids at 2973 cm^{-1} and C-H stretching of polysaccharides at 2902 cm^{-1} was observed in the spectra of pasta samples (Devi et al., 2023). The peak attributed to the stretching of C=O bonds corresponds to the secondary structure of proteins at 1639 cm^{-1}.

Table 5. Textural properties and textural profile analysis of different formulations of pomelo flavedo incorporated pasta

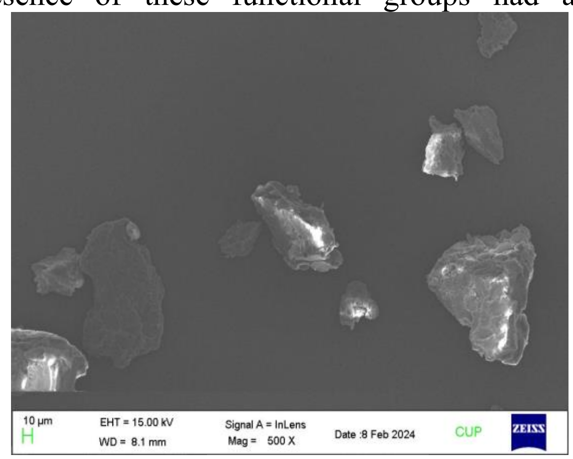
Pomelo pasta concentrations (%)	**Dry pasta**			**Cooked pasta**		**Texture profile analysis (TPA)**					
	Breaking Stress (N/mm^2)	**Fracturability (mm)**	**Stiffness (N/mm^2/sec)**	**Firmness (g)**	**Work of cutting/Toughness (g/sec)**	**Hardness (N)**	**Adhesiveness (g/sec)**	**Springiness**	**Cohesiveness**	**Chewiness (g/cm)**	**Resilience**
Control	6.29±0.12^{a}	7.35±0.21^{a}	47.64±0.42^{a}	678.82±0.29^{a}	584.27±0.55^{a}	84.51±0.31^{a}	-0.97±0.19^{d}	0.92±0.10^{a}	0.59±0.02^{c}	47.35±4.56^{a}	0.55±0.01^{a}
PFP3	5.72±0.19^{b}	6.97±0.09^{b}	39.25±0.78^{b}	584.37±0.52^{b}	564.35±1.66^{b}	78.94±0.61^{b}	-0.96±0.19^{d}	0.84±0.05^{b}	0.60±0.03^{b}	40.82±6.12^{b}	0.44±0.01^{b}
PFP6	4.81±0.16^{c}	6.67±0.08^{c}	36.89±0.42^{c}	486.90±0.98^{c}	477.26±0.53^{c}	74.86±0.78^{c}	-0.77±0.14^{c}	0.75±0.10^{c}	0.62±0.03^{b}	38.30±5.65^{cb}	0.37±0.05^{c}
PFP9	4.61±0.26^{c}	6.49±0.12^{c}	34.82±0.65^{d}	457.83±0.69^{d}	368.87±0.53^{d}	71.11±0.46^{d}	-0.46±0.26^{ba}	0.71±0.09^{c}	0.67±0.06^{b}	29.25±2.27^{d}	0.35±0.03^{c}
PFP12	3.48±0.17^{d}	5.69±0.04^{d}	28.63±0.55^{e}	386.35±0.44^{e}	343.88±0.62^{e}	56.98±0.82^{e}	-0.38±0.02^{a}	0.68±0.04^{d}	0.70±0.08^{a}	25.95±2.08^{ed}	0.32±0.03^{c}

Results are expressed as the mean ± SD (n=3). Values in the same column with different superscripts are significantly different ($p < 0.05$).
PFP: pomelo flavedo pasta

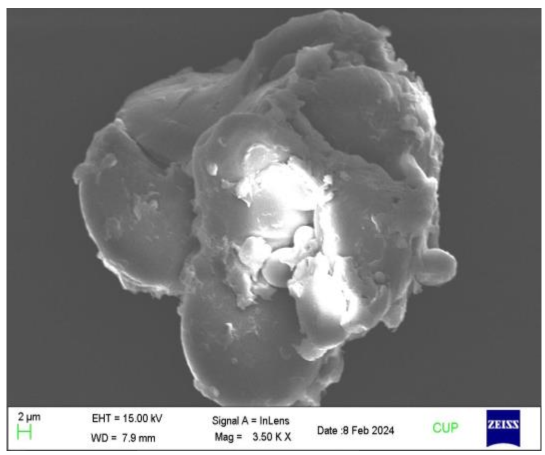
The absorption peak at 1394 cm^{-1} was attributed to O-H bending vibrations. The peak at 1244 cm^{-1} attributed to C(O)–O stretching vibrations and –OH in plane vibrations/amide III indicated the presence of aromatic ethers. The range from 1049 to 1146 cm^{-1} was related to CO-O-CO stretching with anhydride groups (Panda et al., 2024). The stretching of C-O-H vibrations at approximately 997 cm^{-1} is related to the amorphous state of the starch granules. The absorption at 862 cm^{-1} represents the presence of aromatic rings of carbohydrates (Kaur et al., 2023). The 756 and 700 cm^{-1} peaks suggested the presence of C-Cl stretching with an association of alkyl halide and carbohydrates.

The peak from 519 to 556 cm^{-1} indicated stretching due to the presence of halo compounds (Devi et al., 2023). The presence of alkyl halides and aryl halides (halo compounds) are due to the addition of salt in pasta.The presence of these functional groups had a significant impact on the molecular structures of the pasta.

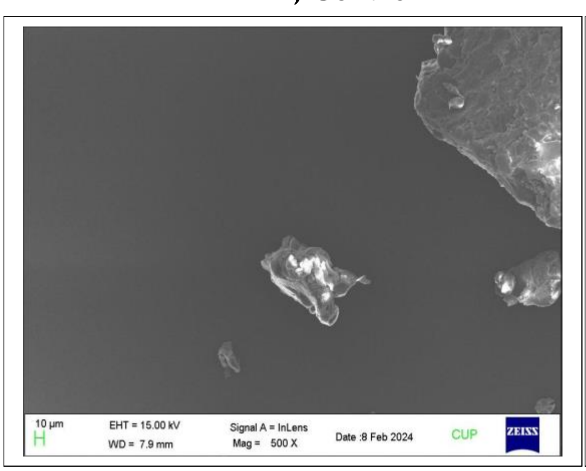
Scanning electron microscopy was used to evaluate the surface morphology and microstructure of the pasta. The structural morphologies of the control, PFP3, PFP6, PFP9, and PFP12 samples are presented in Figure 3. The pasta structure represents the assembly of gluten, protein, and fiber matrix and the variation in their network with an increase in the amount of flavedo powder. The control pasta had a block-shaped structure with a continuous protein-starch network of uniform size and even a uniform surface. The PFP3 and PFP6 samples exhibited large particles of the protein-fiber matrix that were embedded in the surface, which may have caused significant surface cracks and holes.



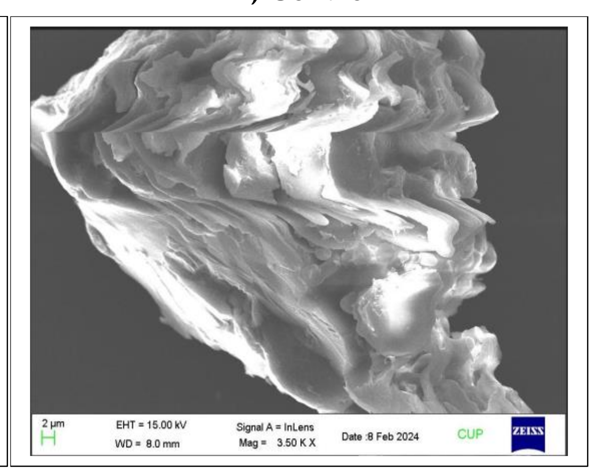
A) Control



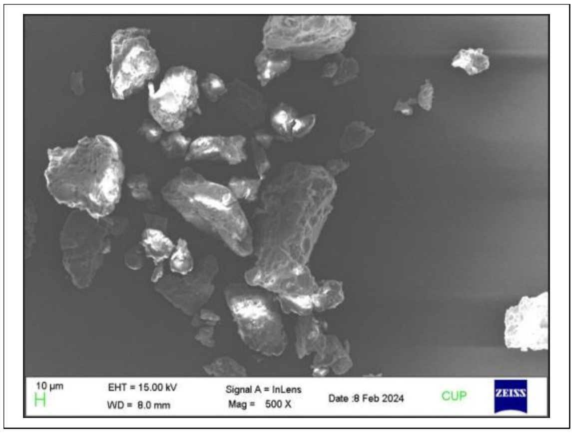
A1) Control



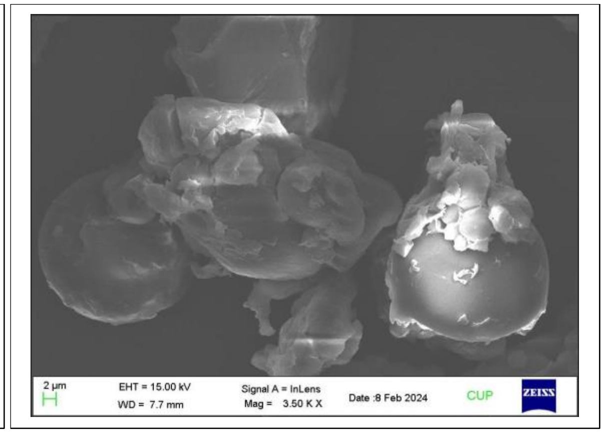
B) PFP3



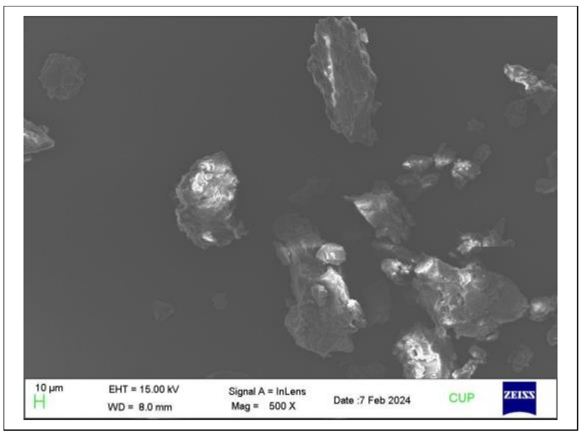
B1) PFP3



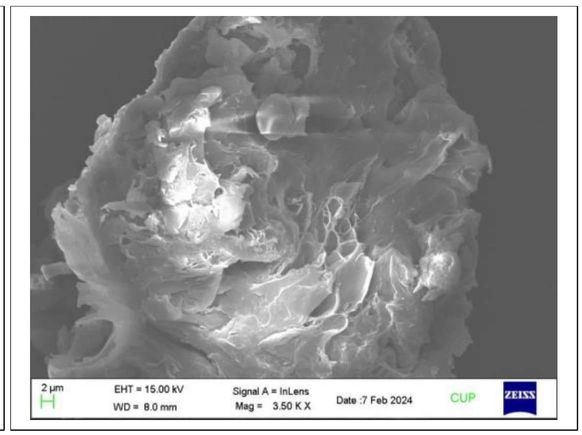
D) PFP9



D1) PFP9



E) PFP12



E1) PFP12

Figure 3. Surface morphology of (A, A1) C, (B, B1) PFP3, (C, C1) PFP6, (D, D1) PFP9, and (E, E1) PFP12 of pomelo flavedo-based pasta

C: Control**; PFP3:** pomelo flavedo pasta 3%; **PFP6:** pomelo flavedo pasta 6%; **PFP9:** pomelo flavedo pasta 9%**; PFP12:** pomelo flavedo pasta 12%

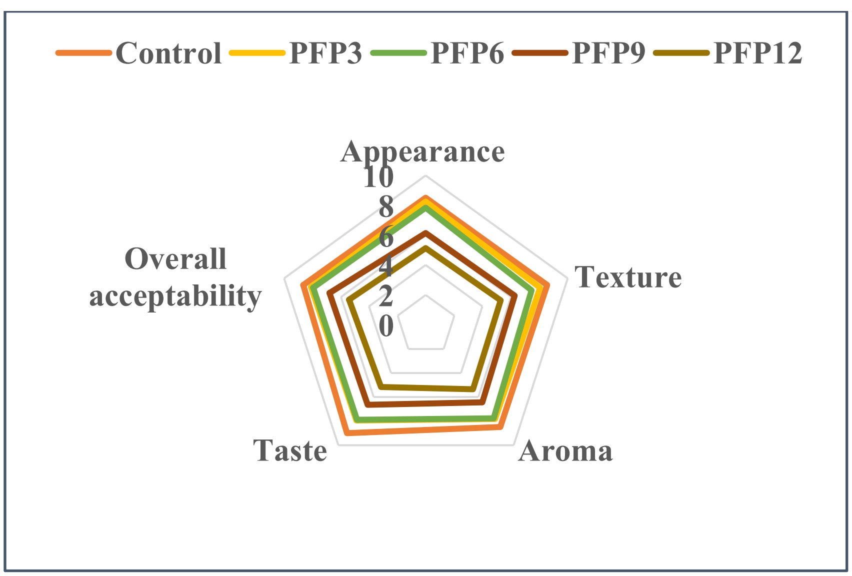


Figure 4. Sensory characteristics of pasta samples with different pomelo flavedo levels (0, 3, 6, 9, and 12%)

The PFP9 sample exhibited the formation of large granule pores in the cell wall and had disarranged fibril bonds. The PFP12 sample showed more irregularities on a non-continuous surface with cracks and granules that allowed starch and fibers to leach out during cooking and hence resulted in more cooking losses and decreased firmness. The addition of pomelo flavedo improves the structure of pasta by maintaining the fiber-gluten network and arrangement of fibrous bonds. Similarly, structural morphology has been reported by Joshi et al. (2023) in maize pasta and by Panda et al. (2024) in Kadamb fruit pasta.

3.8 Sensory evaluation

The results for the sensory attributes of pasta, including appearance, texture, aroma, taste, and overall acceptability, are presented in Figure 4. The sensory evaluation of pomelo flavedo pasta varied significantly ($P<0.05$) as the amount of supplementation with semolina increased. The results showed that pomelo flavedo pasta with 3 and 6% showed good scores for sensory analysis. The sensory evaluation stated that the pasta fortified with 3 to 6% pomelo flavedo had the highest scores for appearance (8.25±0.59 to 7.84±0.72), texture (8.05±0.83 to 7.45±1.01), aroma (7.85±0.47 to 7.75±0.86), taste (7.95±0.60 to 7.89±1.08) and overall acceptability (8.10±0.39 to 7.95±0.72). Pomelo flavedo pasta with 12% showed lower scores for appearance, texture, aroma, taste and overall acceptability. It might be due to the high amount of fiber interfering with the binding of the flour matrix and causing degeneration of the shape, taste profile, textural components, and appearance scores. As the concentration of flavedo powder increased, more fibrous, dark, bitter, and severe solid loss and poor texture pasta were attained, which is unacceptable to consumers.

4. Conclusion and industrial applications

Pomelo flavedo-supplemented pasta is a significant approach for improving the nutritional and antioxidant profiles of samples and provides associated health benefits. The results of the present study indicate that the addition of pomelo flavedo improved the nutritional, bioactive and cooking quality of pasta. It also provides the required natural color to pasta with improved textural and sensory attributes. Pasta with 6% pomelo flavedo powder was found to be more appropriate because it has the desired overall acceptability (7.95), cooking time (9.71 min), cooking loss (4.74%) and nutrient-rich processing with the desired amount of ash, fiber and antioxidants. The supplementation of bioactive constituents in the final product is highly important because it improves the acceptance rate and the physiochemical, textural and sensorial properties of the final product. The production and introduction of such nutritional and functional products in a regular diet can enhance the nutritional status of the population by increasing the safety of various degenerative diseases. Also, the introduction of bioactive enriched pomelo flavedo waste pasta to the food industry is an innovative approach as it offers industrial applications like enhancing nutritional value, extending shelf life, and creating sustainable products, while also focusing on food waste issues.

Future directions

Pomelo fruit peels are a great source of antioxidants, dietary fiber, and other healthy substances. The use of flavedo peel waste to make pasta has promise for the future in terms of improved nutritional content, sustainability, and less food waste. By adding pomelo flavedo peel to pasta, we may solve environmental concerns and provide a novel, nutrient-rich food source. It is a circular economy-promoting and waste-reduction sustainable strategy. The use of flavedo powder in different food items is currently understudied but is a topic of great interest worldwide, therefore future researchers will surely find experimental data valuable as reported in this paper. Additional research at the industrial level is necessary because this study was carried out in a lab. Furthermore, a comprehensive study is required to gain a better knowledge of the relationships between fiber and food items other than pasta to develop a range of high-fiber recipes without compromising food quality or satisfying customer needs.

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Limitations

While utilizing pomelo flavedo peel waste to produce pasta provides nutritional advantages while also reducing waste, there are certain limitations, such as potential changes in texture, color, and flavor, as well as the necessity for careful processing and storage to retain quality.

Data Availability

The authors confirm that the data supporting the findings of this study are available within the article and raw data are on request from the corresponding author.

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Declarations

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Consent to Publish

Not applicable

Ethics Approval
Not applicable

Conflict of interest

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