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Zero-waste valorization of figs in fresh pasta: A sustainable approach to enhance product functionality and quality

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ORIGINAL ARTICLE

Abstract

The zero-waste concept was applied to figs to fortify fresh pasta, using pulp and peels as new ingredients. Two percentages of figs were used, identified as Low (17.55%) and High (20.43%). Technological quality, sensory properties, and fibers were assessed on both control and fortified samples. An *in vitro* digestion was carried out to quantify the amount of released glucose. Results demonstrated that the addition of figs reduced the technological properties of pasta by increasing cooking loss, water absorption, and swelling index. Consequently, a worsening was also observed in sensory acceptability, above all after cooking. However, the new products remained fully acceptable at both concentrations (overall quality = 9.0 for the control, 7.38 for Low, and 6.5 for High). No differences appeared in terms of released glucose with respect to the control (around 2.7 mg/mL glucose released). Interestingly, a significant fortification in insoluble fibers was promoted from 15 in the control to much more than 20 mg/g in fortified pasta. The study demonstrates the complete waste-free production sequence to create healthier pasta. By conferring multifunctional added value, the zero-waste concept actively aligns with circular economy principles and fosters a resilient food future as a promising direction for industrial applications.

Keywords: figs, by-products, fortified pasta, fresh pasta, sustainability, zero-waste

Introduction

The exponential growth of the global population, coupled with the dynamic transformation of the food sector, has led to a significant increase in food waste worldwide (Ganesh *et al.*, 2022). Among the different proportions of wasted food materials, fruit and vegetable by-products make up a significant percentage (42%). By-products include edible and inedible parts rich in many bioactive compounds, such as dietary fibers, vitamins, and various phytochemicals such as carotenoids, flavonoids, and phenolic acids, known to exhibit antioxidant, antimicrobial, or anti-inflammatory activities (Gowe, 2015; Faria, 2023; Yusuf, 2017). For this reason, by-products from red grape marc, broccoli, peppers, tomatoes, *etc.* have been valorized in food items as new ingredients for food fortification (Lucera *et al.*, 2018; García-Lomillo, 2014; Teterycz & Sobota, 2023) or are found suitable as flavorings and preservative compounds (Pereira, 2022; Shinali *et al.*, 2024). The incorporation of by-products in food formulation represents not only a significant advancement towards the development of functional products (Zahid & Khedkar, 2021; Sanjuán-Ferrer *et al.*, 2023) but also lies precisely in the valorization of residual horticultural matrices, transforming these environmental burdens into valuable resources according to circular economy principles (Darko *et al.*, 2024; Pereira *et al.*, 2022; Sarker *et al.*, 2023; Le Rose *et al.*, 2025). However, when agri-food by-products are recycled, some residual waste can still be generated, especially after extractions from by-products. Therefore, it is essential to develop strategies that minimize residual waste by valorizing the entire raw material, according to the so-called zero-waste approach that can promote circular economy and environmental sustainability (Taheri *et al.*, 2025). The zero-waste is a growing movement that aims to reduce waste production, promote sustainable consumption, and preserve the environment. From small-scale initiatives to large-scale projects, there are several inspiring examples of zero-waste projects around the world. This approach focuses on optimizing the management of products and processes to prevent waste generation and enable resource recovery (Mohan *et al.*, 2020; Panza *et al.*, 2022a). In this perspective, Marinelli *et al.* (2021) developed a watermelon-based jelly candy fortified with all parts of the fruit (rind, pulp, and juice), further enriched with albedo and flavedo from orange fruits. Similarly, Romano *et al.* (2020) proposed a new type of tomato puree, richer in phenolic compounds and volatile organic compounds, produced from the whole fruit. Another example of the zero-waste approach is the production of muffins using pulp and peel from banana, with enhanced antioxidant activity and a high content of bioactive compounds (Soto-Maldonado *et al.*, 2020).

In this context, fig fruit plays a key role for several reasons. Figs are highly perishable due to early senescence, fermentation phenomena, and fungal decay. It is worth considering that the industrial processing of figs to produce juice, puree, or jam generates significant amounts of by-products (Teruel-Andreu *et al.*, 2021). Additionally, a portion of harvested fruits is often rejected due to mechanical damage occurring during handling and transport (Taghavi *et al.*, 2023). Therefore, the possibility of recovering the entire fruit could be a strategic approach to avoid the loss of valuable resources. Fig is a fruit rich in minerals, vitamins, and dietary fiber. It is naturally fat- and cholesterol-free and is also characterized by a high amino acid content (Slavin, 2006; Solomon *et al.*, 2006). Like many other fruit species, figs contain sugars and organic acids (Veberic *et al.*, 2008).

A few applications of fig by-products in food are reported. Fig seed pomace was used as an ingredient in gluten-free cupcakes (Takma, Balçık, & Sahin-Nadeem, 2021), and fig peels were applied as a natural preservative for fresh pasta (Panza, 2022b). While several studies address the general valorization of fruit by-products, research specifically focusing on the valorization of entire figs to prevent food loss remains very scarce. Due to this gap, the novelty of the current paper lies in the application of the zero-waste concept to entire figs, considering both pulp and peels as new valid ingredients for fresh pasta fortification. The objective was to demonstrate how the integration of the entire fig fruit increased the fiber content of pasta while maintaining sensory acceptability and technological properties. Through simulated *in vitro* digestion, the potential metabolic modifications induced by the ingestion of the enriched pasta were also assessed by quantifying the amount of glucose released.

Materials and Methods

Pulp and peel fig preparation

Fresh fig fruits (*Ficus carica* L.) were supplied by a local dealer (Foggia, Italy) and transported to the laboratory. The fruits were washed with water to remove any solid residues and immersed in chlorinated water (20 mL/L) for 5 min. Subsequently, they were rinsed with water and air-dried. A lab extractor (Hurom, Italjuicer Srl, Verona, Italy) was then used to separate the pulp from the peels. The pulp was stored under freezing conditions before use, whereas the peels were dehydrated. Dehydration was carried out in a hot air conventional dryer (PF–SICCO80PRO, SICCOTECH, Campobasso, Italy), with a cabinet volume of 0.6 m3. Atmospheric pressure, relative humidity of 5%, and a temperature of 50 °C were set. Periodically, the sample weight (5 g) was measured using a thermal balance (Sartorius, Gottingen, Germany) set at 130 °C, and when it remained constant for several consecutive measurements, the dehydration process was stopped. The process lasted about 48 h. The final moisture content of the dried fig peels was about 7%. The dried peels were ground in a lab grinder (KMEC Engineering, Kate Road, Anqiu City, China), obtaining a very fine powder (< 500 μm), which was stored in plastic bags at 4 °C, protected from light.

Pasta production

Semolina and eggs were purchased from a local market in Foggia (Italy). The control pasta dough was prepared by mixing durum wheat semolina (1035 g) with water (270 g) and fresh pasteurized eggs (195 g) in an extruder (Monferrina P3, Lineapasta, Italy) for about 7 min (Ctrl). For the two fortified samples, named Low and High, the pulp was previously defrosted under refrigerated conditions and then used to hydrate the peel powder. Both these ingredients partially substituted the three main pasta ingredients. For the Low sample, 36 g of fig peel powder were hydrated with 245 g of fig pulp; for the High sample, 43 g of peel powder were hydrated with 291 g of fig pulp. After hydration, the ingredients were added to the rest of the dough, and after proper mixing, the dough was extruded from the machine using a special die to form pasta in the shape of *troccoli*. Three different formulations were prepared: dough without any addition of figs (Ctrl) and two types with increasing concentrations of fig pulp and corresponding peel powder, reaching a total fig percentage weight fraction equal to 17.55% in the Low formulation and 20.43% in the High recipe. Preliminary tests were carried out to select the range of figs (pulp and peel powder) to be included in the dough to obtain an acceptable pasta (data not published). According to the zero-waste approach, the amount of peel powder corresponded to the exact grams of peels generated from the selected grams of pulp. Table 1 reports the percentage weight fractions of each ingredient. A visual diagram displays the complete waste-free production sequence, from raw material acquisition to product enrichment (Figure 1).

Pasta cooking quality

The assessment of the main quality parameters (cooking loss, swelling index, and water absorption) was determined according to the approved method AACC 66-50 (2000). The cooking loss (%) corresponds to the solids lost in the cooking water. To measure the cooking loss, pasta samples (10 g) were cooked at the optimum cooking time (OCT) in 300 mL of distilled water. The cooking water was then collected in an aluminum container, placed in an oven at 105 °C, and evaporated until a constant weight was reached. The residue was weighed and reported as a percentage of the starting material. The swelling index was determined according to the procedure described by Cleary and Brennan (2006). Therefore, each sample (10 g) was cooked (taking OCT into account) and subsequently dried at 105 °C until a constant weight was reached. The swelling index was expressed as [(weight of cooked sample) – (weight of sample after drying) / weight of sample after drying]. The water absorption (%) of the drained samples was determined as [(weight of cooked sample) – (weight of raw sample)/(weight of raw sample)]•100. All the measurements were performed in triplicate.

Sensory analysis of pasta

A quantitative descriptive analysis (QDA) was used to compare the samples from the sensory point of view.

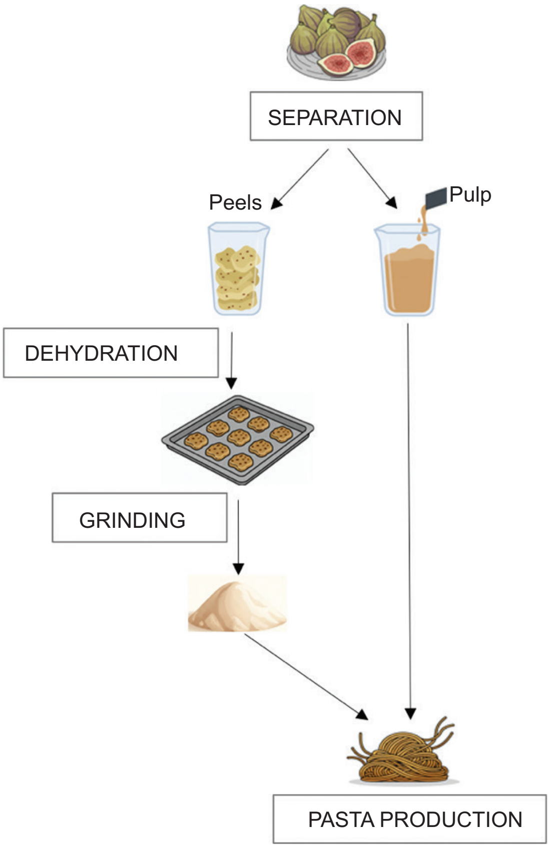

Figure 1. Diagram to display the separation of figs in pulp and peels, the peel dehydration and grinding and the subsequent addition of both pulp and peel powder to pasta formulation.

Table 1. Percentage weight fractions of all the ingredients used for the control and fortified pasta samples.

Ingredients	CTRL [%]	Low [%]	High [%]
Durum wheat semolina	69	64.64	63.34
Water	18	5.62	4.28
Eggs	13	12.18	11.93
Fig pulp	0	15.30	17.81
Fig peel powder	0	2.25	2.62

CTRL = control pasta; Low = pasta with 17,55% of figs as pulp and peels; High = pasta with 20,43% of figs as pulp and peels.

The guidelines of the Codex Alimentarius Commission were precisely followed. The samples were submitted to a panel of seven trained judges with several years of experience in fresh pasta sensory evaluation before the current study. They were researchers and Ph.D. students of the Department of Food Science at the University of Foggia. To align their judgments and define the sensory parameters, the panel members were re-trained in a new session for 2 days (1 h/day). During the test, they were asked to indicate odor, color, homogeneity, breaking strength, and appearance of fresh raw samples and odor, color, elasticity, firmness, and taste of fresh cooked *troccoli*. In addition, each member was asked to score the overall quality of both raw and cooked pasta. For the evaluation, a 9-point scale was used (1 = lowest score; 9 = highest score; 5 = threshold of acceptability). The experiment did not require any Ethics Committee approval because there were no risks associated for the panelists. The samples were prepared according to good manufacturing practices. For protecting the rights and privacy of the participants on the panel, an appropriate protocol was adopted to consider the verbal consent of the participants, no coercion to participate, the ability to withdraw from the study at any time, full disclosure of study requirements and risks, and non-release of participant data without their knowledge.

Dietary fiber determination

Total, soluble, and insoluble dietary fiber contents were determined using a commercial kit assay (Total Dietary Fiber Assay Kit, Supelco, Sigma-Aldrich, St. Louis, MO, USA), following the producer's instructions.

Enzymatic breakdown

Before determining the total, soluble, and insoluble fiber content, each pasta sample was subjected to an enzymatic breakdown treatment. For this purpose, 1.0 g of modified or control pasta was weighed into two 400-mL beakers. To each beaker, 40 mL of MES/TRIS (0.055/0.05 M) buffer solution (pH 8.3) were added, followed by 50 μL of α-amylase solution, and the samples were incubated under stirring for 30 min at 95 °C. After cooling to 60 °C, 50 μL of protease solution were added, and the incubation continued for 30 min at 60 °C. Then, 5 mL of 0.56 M hydrochloric acid were added, and the pH was adjusted to 4.0–4.7 using either 5% sodium hydroxide or 5% hydrochloric acid. Finally, 150 μL of amylo-glucosidase solution were added, and the samples were incubated for a further 30 min at 60 °C.

Determination of total dietary fiber

For each pasta sample, to one of the two beakers in which the enzymatic digestion was performed (paragraph 2.5.1), 220 mL of 95% ethanol previously heated to 60 °C were added. The formed precipitate was allowed to settle for at least 1 h at room temperature and then recovered by centrifugation at 7000 rpm for 10 min. The collected precipitate was washed with 3 × 15 mL of 78% ethanol, followed by 2 × 10 mL of 95% ethanol and 3 × 10 mL of acetone. Finally, it was dried at 105 °C overnight and weighed for the determination of total fiber content.

Determination of soluble and insoluble dietary fiber

For the determination of soluble and insoluble fibers, the mixture from the other beaker from the enzymatic digestion of each pasta sample (paragraph 2.5.1) was centrifuged at 7000 rpm for 10 min. The beaker was then washed twice with 10 mL of water previously heated to 70 °C. The combined supernatant and washings were transferred to another beaker, whereas the solid residue was washed with 2 × 15 mL of 78% ethanol, 95% ethanol, and acetone, and finally dried overnight at 105 °C and weighed for the determination of insoluble fiber content. For the determination of the soluble fiber content, to the combined supernatant and washings, four volumes of 95% ethanol (previously heated to 60 °C) were added. The precipitate formed was allowed to settle for at least 1 h at room temperature. Subsequently, the mixtures were centrifuged at 7000 rpm for 10 min and washed with 3 × 15 mL of 78% ethanol, followed by 2 × 10 mL of 95% ethanol and 3 × 10 mL of acetone. The samples were dried overnight at 105 °C and then weighed for the quantification of soluble fiber content.

Pasta glycemic index

In vitro digestion protocol

The *in vitro* digestion protocol was based on previously developed procedures, with slight modifications (Argyri *et al.*, 2016). For the oral phase, 1 g of cooked pasta sample was mixed with an equal weight of distilled water, homogenized, and incubated with α-amylase (75 U/mL) at 37 °C for 15 min under stirring. Subsequently, 1 mL of pepsin solution (1100 U/mL) was added, and the pH was adjusted to 2.5 using 0.1 M HCl. The samples were incubated at 37 °C for 2 h, after which 2 mL of 0.1 M PIPES buffer (pH 6.5) was added. Then, 10 μL of an amylo-glucosidase solution (3260 U/mL) and 0.5 mL of a pancreatin–bile salt mixture, prepared by suspending 0.2 g of porcine pancreatin and 1.2 g of bile extract in 100 mL of 0.1 M $NaHCO_3$, were added. The samples were incubated at 37 °C under stirring for 2 h. At the end of the digestion process, 0.2 mL aliquots of the digested samples were immediately mixed with 0.8 mL of ethanol. After 30 min, the mixtures were centrifuged at 5000 rpm for 10 min at 20 °C. The supernatants were stored at −20 °C before further analysis.

Dinitrosalucylic (DNS) assay for glucose determination

The DNS reagent solution was prepared by dissolving 10 g of 3,5-dinitrosalicylic acid, 2 g of phenol, 0.5 g of sodium sulfite, and 10 g of sodium hydroxide in 1 L of distilled water. For the assay, 2 mL of the DNS reagent were added to a glucose standard solution (10 mg/mL in water) or 60 µL of digested samples in a test tube. The mixtures were then heated at 90 °C for 5 min, until the development of the red-brown color. After that, 333 µL of a 40% (w/w) potassium sodium tartrate aqueous solution was added to stabilize the color. The samples were cooled to room temperature in a cold-water bath, and the absorbance was measured at 575 nm using a spectrophotometer. All experiments were performed in triplicate (Englyst, 1987).

Statistical analysis

For each pasta type, three replicates were prepared to ensure statistical robustness. The experimental data were compared using a one-way ANOVA analysis of variance with JMP 18. Tukey's HSD test, with the option of homogeneous groups ($p < 0.05$), was carried out to determine significant differences among the samples. JMP 18 for Windows (JMP Statistical Discovery LLC, 920 SAS Campus Drive, Cary, NC 27513) was used.

Results and Discussion

Technological properties

The technological properties of *troccoli* are listed in Table 2. As shown in the table, with the increase in the amount of fig pulp and powder, a worsening in technological properties was observed. However, it should be noted that the differences are statistically significant ($p<0.05$) only for cooking loss, while for the other two indexes, the differences among samples are not statistically significant ($p>0.05$). In general, pasta containing by-products tends to show greater weight loss during cooking, whereas the observed differences in swelling index and water absorption are less clear. Gómez *et al.* (2025), discussing the effect of plant-based by-product addition on the technological quality of pasta, underlined that comparisons among studies in the literature are not always possible because the water absorption outcomes of pasta largely depend on the water absorption capacity of the by-product. In addition, the authors specified that it is also necessary to consider dough hydration, since higher dough hydration results in lower water absorption during cooking. Thus, studies that adjust dough hydration based on the by-product's water absorption capacity observed lower water absorption during cooking compared to those that do not adjust hydration.

The technological worsening found in the current study is due to the reduction in the strength of the gluten network. The reason for this is twofold: on one hand, the amount of durum wheat semolina was reduced as the concentration of fig pulp and powder increased; on the other hand, the fig powder interfered with the formation of the gluten network, most probably due to the sugars present in the fig pulp (Zang *et al.*, 2022; Foschia *et al.*, 2015). Dietary fibers of figs can interfere with the integrity of the protein–starch network and provoke uneven water distribution within the matrix due to their competitive hydration tendency (Tudorică, Kuri & Brennan, 2002). Similar results were reported by Lu *et al.* (2016), who demonstrated a significant increase in cooking loss with increasing levels of mushroom powder in pasta compared to a control sample made of traditional semolina. Likewise, Zhao *et al.* (2005) reported an increase in the cooking loss of spaghetti containing a high content of legume flour. The continuity and strength of the protein matrix progressively disintegrated during cooking, leading to the release of starch granules that gelatinize. This phenomenon contributes to increased cohesiveness and stickiness on the cooked pasta surface (Sissons, 2008). Nevertheless, a cooking loss of up to 12% is generally considered acceptable and indicative of good-quality pasta (Espinosa-Solis *et al.*, 2019).

Table 2. Technological properties of the control and fortified pasta samples.

Sample	Cooking loss [%]	Water absorption [%]	Swelling index
CTRL	2.57 ± 0.25^b	58.87 ± 3.14^a	1.69 ± 0.07^a
Low	4.53 ± 0.47^a	77.73 ± 7.88^a	1.72 ± 0.12^a
High	4.65 ± 0.76^a	79.40 ± 10.99^a	2.25 ± 0.43^a

Data are means ± standard deviations. Data in each column with different superscript letters are statistically different ($p<0.05$). CTRL = control pasta; Low = pasta with 17,55% of figs as pulp and peels; High = pasta with 20,43% of figs as pulp and peels.

Sensory evaluation

The sensory attributes of uncooked *troccoli* are shown in Table 3. The data show a decrease in overall quality as the fig content increased. A decline in sensory quality is quite common when unconventional ingredients such as by-products are incorporated into traditional recipes (Darko *et al.*, 2024; Carpentieri *et al.*, 2022). However, it should be noted that the differences observed in the current study between the overall quality of the Ctrl sample and that of the fortified pasta were statistically significant ($p < 0.05$) only for the sample with the highest concentration of figs (High sample). Considering the individual sensory parameters, it is worth noting that the attribute *resistance to breaking* played a key role. This parameter is closely related to the strength of the gluten network and steadily decreased as the fig concentration increased (Sant'Anna *et al.*, 2014). The scores for *appearance* and *homogeneity* of *troccoli* were slightly reduced in the two fortified samples, but these changes do not appear to be of major importance compared to the control pasta (Jhan *et al.*, 2025). Similarly, the sensory attributes *color* and *odor* were found to be very similar to the control ($p > 0.05$). These findings align with existing literature. For instance, Sant'Anna *et al.* (2014) reported that the substitution of wheat flour with grape marc powder led to decreased *appearance, color,* and *overall acceptance* of pasta. Similarly, Sobota *et al.* (2015) demonstrated that the inclusion of wheat bran in pasta formulations significantly altered the *appearance.*

Data shown in Table 4 indicate the sensory quality of cooked pasta. The results show that the overall quality was affected by the presence of figs in a much more pronounced way than in the raw samples. In fact, the addition of figs altered the attributes directly related to the strength of the gluten network (i.e., *elasticity*, *adhesiveness*, and *firmness*) (Foschia, 2015), as well as those not associated with network modification (i.e., *taste*). Scientific literature supports these findings, particularly when by-products rich in fiber are added at concentrations equal to or higher than 15% (Bianchi *et al.*, 2021). A similar response was reported by Cedola *et al.* (2020), who incorporated olive paste and olive mill waste into pasta. The substitution of semolina with olive by-products significantly compromised the pasta profile in terms of *elasticity, firmness, and bulkiness,* due to alterations in the gluten network (Cedola *et al.*, 2020).

Concerning *taste*, data from the literature confirm that the addition of new ingredients derived from agri-food by-products, particularly peels, can affect sensory perception due to the presence of bitter compounds (Padalino *et al.*, 2017; Pan *et al.*, 2018). Crizel *et al.* (2015) evaluated the sensory properties of pasta enriched with orange by-products and found that increasing levels of incorporation decreased consumer acceptance because of changes in taste and aftertaste.

It is worth noting that some sensory attributes of cooked *troccoli* are closely related to the technological properties, as both depend on the strength of the gluten network (Rakhesh *et al.*, 2015). Figure 2 shows *adhesiveness* plotted as a function of cooking loss. It should be noted that the curve in the figure was drawn

Table 3. **Sensory quality of raw control and fortified pasta samples.**

Sample	Color	Odor	Homogeneity	Resistance to breaking	Appearance	Overall quality
Ctrl	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}
Low	8.75 ± 0.50^{a}	8.63 ± 0.25^{a}	8.25 ± 0.29^{b}	8.50 ± 0.1^{b}	8.88 ± 0.25^{a}	8.88 ± 0.25^{a}
High	8.63 ± 0.25^{a}	8.88 ± 0.25^{a}	8.50 ± 0^{b}	8.0 ± 0.1^{c}	8.25 ± 0.29^{b}	8.38 ± 0.25^{b}

Data are means ± standard deviations. Data in each column with different superscript letters are statistically different (p<0.05). CTRL= control pasta; Low = pasta with 17,55% of figs as pulp and peels; High = pasta with 20,43% of figs as pulp and peels.

Table 4. **Sensory quality of cooked control and fortified pasta samples.**

Sample	Color	Odor	Elasticity	Bulkiness	Adhesiveness	Firmness	Taste	Overall quality
CTRL	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}	9.0 ± 0.1^{a}
Low	8.5 ± 0^{b}	8.5 ± 0^{b}	8.25 ± 0.29^{b}	7.0 ± 0.1^{b}	6.88 ± 0.25^{b}	6.88 ± 0.25^{b}	7.50 ± 0^{b}	7.38 ± 0.25^{b}
High	8.5 ± 0^{b}	9.0 ± 0.1^{a}	7.0 ± 0.1^{c}	6.38 ± 0.48^{b}	6.13 ± 0.25^{c}	6.13 ± 0.25^{c}	6.75 ± 0.29^{c}	6.50 ± 0.1^{c}

Data are means ± standard deviations. Data in each column with different superscript letters are statistically different (p<0.05). CTRL = control pasta; Low = pasta with 17,55% of figs as pulp and peels; High = pasta with 20,43% of figs as pulp and peels.

solely to highlight the trend of the data. The curve indicates that as cooking loss increased, *adhesiveness* decreased. This observation suggests that the starch (especially amylopectin) content in the pasta cooking water increased. As the amount of starch lost from pasta rises, the quantity accumulating on its surface also increases, and consequently, the sensory attribute related to *adhesiveness* decreases (Aravind *et al.*, 2012). Rakhesh *et al.* (2015) also reported that pasta *adhesiveness* can result from water absorption by certain fibers, which form a viscous layer on the pasta surface. Consistent with our findings, Bianchi *et al.* (2024), who studied fresh pasta enriched with red chicory by-product powder, observed that both cooking loss and *adhesiveness* measured by a texture analyzer increased proportionally with fortification.

Figure 3 shows the *bulkiness* plotted as a function of cooking loss. As in the previous case, the curve shown in the figure was drawn only to highlight the data trend. As can be seen, a decrease in *bulkiness* was observed as the cooking loss increased. This result was expected, since *bulkiness* is closely related to the amount of starch present on the pasta surface. Therefore, the same considerations made for *adhesiveness* can be applied to *bulkiness*.

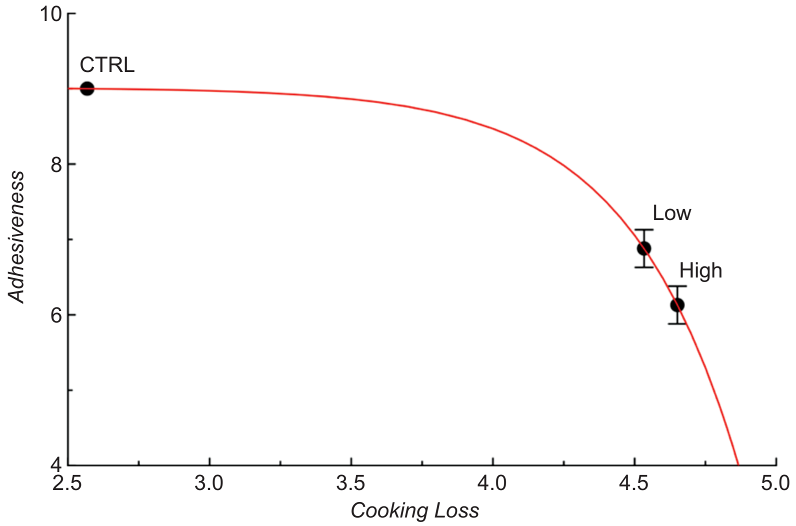

Figure 2. ***Adhesiveness*** **plotted as a function of cooking loss for control and fortified pasta samples. CTRL= control pasta; Low = pasta with 17,55% of figs as pulp and peels; High = pasta with 20,43% of figs as pulp and peels.**

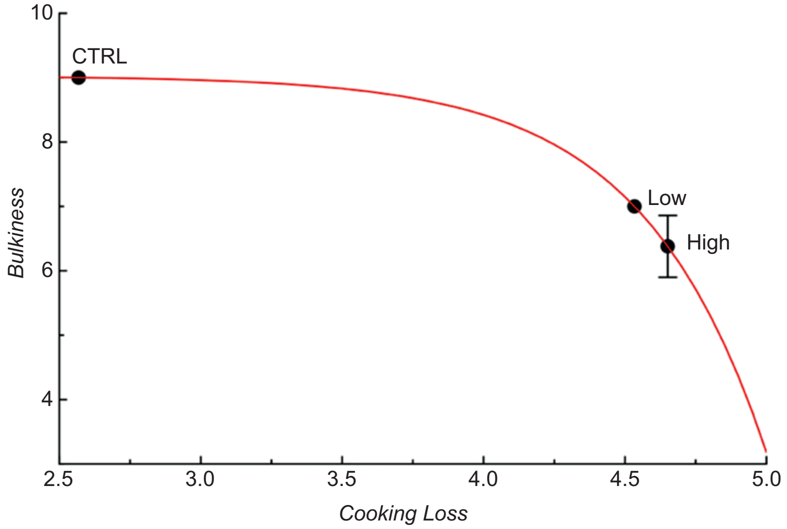

Figure 3. ***Bulkiness*** **plotted as a function of cooking loss for control and fortified pasta samples. CTRL = control pasta; Low = pasta with 17,55% of figs as pulp and peels; High = pasta with 20,43% of figs as pulp and peels.**

Figure 4 shows the *firmness* plotted as a function of the water absorption index. As before, the curve shown in the figure was drawn to underline the trend of the data. A decrease in the sensory attribute was observed as the water absorption index increased. In this case, *firmness* is a measure of the resistance of cooked pasta to compression. The reduction in *firmness* demonstrates a weak gluten network (Gómez *et al.*, 2025). Therefore, *firmness* is closely related to the amount of water absorbed by the *troccoli* during cooking. As the latter increased, the *firmness* was expected to decrease (Nilusha *et al.*, 2019). Carpentieri *et al.* (2022), in a comprehensive and up-to-date overview on pasta functionalization through the addition of agri-food by-products, thoroughly discussed these drawbacks. These authors reported that the incorporation of by-product ingredients led to crucial changes in the technological characteristics of pasta, such as increased water uptake and consequently reduced pasta *firmness*.

Fiber content

The determination of dietary fiber content was carried out with the aim of evaluating the impact of fig addition on the nutritional profile of pasta. Dietary fibers, divided into soluble and insoluble fractions, play a fundamental role in promoting gastrointestinal and metabolic health, thus contributing to the regulation of intestinal transit, control of postprandial glycaemia, and modulation of the microbiota (Anderson *et al.*, 2009; Elleuch *et al.*, 2011; Li & Ma, 2024). The inclusion of figs, known for their high fiber content, was indeed designed also to enrich pasta with natural functional components, thereby improving its nutritional value. As reported in Table 5, the enrichment of pasta with fig samples led to a significant improvement in the total dietary fiber content. An increase from 52 ± 3 mg/g in the control pasta to 61 ± 3 mg/g and 60 ± 5 mg/g in the High and Low samples, respectively, was observed. The significant increase in total fiber can be mainly attributed to the insoluble fraction, which increased from 15 ± 1 mg/g in the control sample to 23 ± 4 mg/g (High) and 27 ± 6 mg/g (Low) ($p < 0.05$). No significant differences were observed in the soluble fiber content ($p > 0.05$). This trend suggests that fig powder may act as an important source of insoluble fibers such as cellulose, hemicellulose, and lignin (Sandhu *et al.*, 2023). These findings demonstrate that the use of fig pulp and peel powder

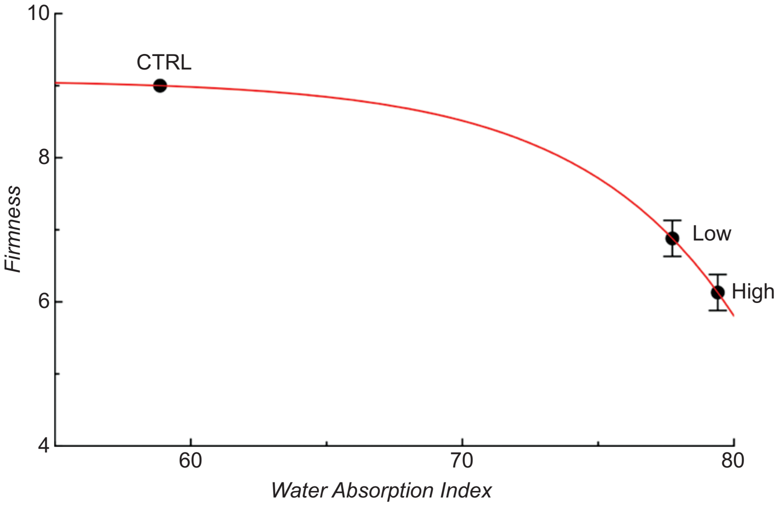

Figure 4. ***Firmness*** **plotted as a function of water absorption index for control and fortified pasta samples. CTRL= control pasta; Low = pasta with 17,55% of figs as pulp and peels; High = pasta with 20,43% of figs as pulp and peels.**

Table 5. Dietary total, insoluble and soluble fiber content of fresh pasta with and without figs.

Sample	Total fibers (mg/g of pasta)	Soluble fibers (mg/g of pasta)	Insoluble fibers (mg/g of pasta)
CTRL	52 ± 3^{a}	37 ± 1^{a}	15 ± 1^{a}
Low	60 ± 5^{a,b}	35 ± 4^{a}	27 ± 6^{b}
High	61 ± 3^{b}	36 ± 1^{a}	23 ± 4^{b}

Data are means ± standard deviations. Data in each column with different superscript letters are statistically different (p<0.05). CTRL= control pasta; Low = pasta with 17,55% of figs as pulp and peels; High = pasta with 20,43% of figs as pulp and peels.

Table 6. Glucose released during *in vitro* digestion of fresh pasta prepared with and without fig addition.

Sample	Glucose released [mg/mL]
CTRL	2.6 ± 0.1^{a}
Low	2.7 ± 0.1^{a}
High	2.7 ± 0.1^{a}

Data are means ± standard deviations. Data in each column with different superscript letters are statistically different ($p<0.05$). CTRL= control pasta; Low = pasta with 17,55% of figs as pulp and peels; High = pasta with 20,43% of figs as pulp and peels.

not only represents a valorization of agro-industrial by-products, but also allows pasta to meet current nutritional needs, such as increasing fiber intake (recommended 25–30 g/day) and controlling postprandial blood sugar levels (Elleuch *et al.*, 2011). Considering the benefits of fiber intake and the fact that dietary fiber consumption remains far below the recommended level in modern societies, the results of the present study may attract attention from the industrial sector, which is showing strong interest in developing fiber-enriched food products by incorporating fruits into meals (Sarker & Rahman, 2017).

Glycemic index

To explore the potential metabolic modifications induced by the ingestion of fig-enriched pasta, a simulated *in vitro* digestion was performed to quantify the amount of glucose released from the pasta samples. These data provide insight into the potential glycemic response induced by both modified and unmodified pasta. As reported in Table 6, no significant differences were observed in the amount of released glucose after simulated gastrointestinal digestion between the High and Low fig-enriched samples and the control pasta. Considering the high sugar content of fig pulp (Yang *et al.*, 2023; Solomon *et al.*, 2006), which could potentially increase the glycemic response of fortified pasta, this result appears unexpected. However, it can be interpreted in light of the high levels of insoluble fiber in figs, which may act as a physical barrier to sugar release during digestion (Elleuch *et al.*, 2011).

Conclusions

For the first time, the zero-waste concept was applied to the complete recycling of figs in the production of artisanal fresh pasta. The fruit was processed to separate the pulp from the peel, with the latter dehydrated at 50 °C and ground into powder. Two inclusion levels of fig pulp combined with peel powder (17.55% and 20.43%) were tested, resulting in fortified pasta samples referred to as Low and High. The technological quality and sensory acceptability analyses revealed that the addition of fig-derived ingredients affected pasta characteristics, although the products remained acceptable. The gluten network strength was weakened due to the reduced proportion of semolina, and the sensory properties of cooked pasta were more influenced than those of raw samples, particularly in terms of *adhesiveness* and *bulkiness*. A negative correlation between *firmness* and water absorption index was also found. The inclusion of figs slightly affected the taste, and overall acceptability decreased from 9.00 in the control to 7.38 ± 0.25 and 6.50 ± 0.10 in Low and High samples, respectively. Conversely, the enrichment with fig pulp and peel significantly increased the total dietary fiber content, mainly the insoluble fraction, without influencing the glucose released after *in vitro* digestion, suggesting a favorable balance between improved nutritional profile and metabolic response. These findings demonstrate that fig pulp and peel, often discarded as waste, can be effectively valorized as functional ingredients in pasta, contributing to both waste reduction and nutritional enhancement while promoting sustainable production practices.

A comprehensive evaluation, spanning sensory analysis, nutritional evaluation, and environmental impact could provide a holistic assessment of the developed formulations. The study successfully establishes a proof of concept for a circular economy model within the food industry, where waste is minimized and resources are maximized.

In conclusion, this study confirms the potential of using fig pulp and peels to fortify pasta, offering clear nutritional advantages while promoting sustainable food production. However, the economic feasibility of this process requires further evaluation and optimization. In particular, the energy demand associated with peel drying and its related costs must be substantially reduced to make this innovative upcycling approach competitive with conventional ingredients. Future research should therefore focus on improving the energy efficiency of dehydration techniques and investigating alternative valorization strategies to lower production expenses, ultimately supporting the broader implementation of this circular food innovation.

Data Availability

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Author Contributions

C.R.: formal analysis and writing—original draft; F.M.: formal analysis and writing—original draft; L.P.: conceptualization, data curation, writing—original draft; A.C.: conceptualization, writing—review and editing, and supervision; M.A.D.: conceptualization, data curation, writing—original draft. All the authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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