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Upcycling of tomato by-products in food: quality improvements and life cycle assessment

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This study investigates the upcycling of tomato peels and seeds (TPSs) as functional ingredients for fortifying pasta and gnocchi within a circular bioeconomy framework. The incorporation of TPSs resulted in marked nutritional enhancements, with total dietary fiber increasing by up to much more than 100% in both pasta and gnocchi, and significant improvements in antioxidant activity (ABTS and FRAP assays) and bioactive compounds such as polyphenols and flavonoids (increases of up to ∼20–60% depending on formulation). Despite minor sensory changes associated with TPS addition, all formulations retained acceptable scores (>5 on a 9-point scale), indicating that acceptability was preserved even at the highest enrichment levels. Notably, the impact on sensory quality was limited and formulation-dependent, with optimized samples successfully balancing technological feasibility and palatability. From an environmental perspective, Life Cycle Assessment (LCA) showed that the energy demand associated with additional processing steps (drying and milling) partially offsets the environmental benefits, particularly in terms of Global Warming Potential (GWP). However, the incorporation of TPSs still supports the valorization of agro-industrial by-products and compensates for the reduced use of conventional raw materials. The integration of sensory, nutritional, and environmental indicators through the Global Quality Index (GQI) demonstrated a clear net positive balance for all TPS-enriched samples. In particular, gnocchi showed the highest overall performance, confirming their suitability as a carrier for TPS incorporation. These findings demonstrate that TPS upcycling represents an effective and sustainable strategy to develop nutritionally enhanced staple foods, supporting waste valorization while retaining satisfactory sensory quality.

Sustainability spotlight

The upcycling of tomato peels and seeds into fortified pasta and gnocchi directly supports the UN 2030 Agenda. This approach contributes to SDG 12 (Responsible Consumption and Production) by valorizing food-processing by-products and reducing waste and to SDG 2 (Zero Hunger) by improving the nutritional quality of staple foods through increased fiber and antioxidants. Despite higher energy demands during processing, the overall positive global quality index highlights how circular bioeconomy strategies can align food innovation with sustainable, resilient production systems.

1 Introduction

About one-third of all food produced globally is lost or wasted along the entire food supply chain,[1] which has substantial negative environmental, social, and economic impacts.[2] Indeed, the reduction of this quantity is one of the Sustainable Development Goals (SDGs) established by the 2030 Agenda.[3] Globally, the highest food losses occur in roots, tubers, and oil-bearing crops (25%), followed by fruits and vegetables (22%), while in Europe, fruits and vegetables represent the food items with the greatest amount of waste.[4]

Tomato (*Solanum lycopersicum* L.) is one of the most cultivated and processed vegetables globally and constitutes a fundamental pillar of the Mediterranean diet. Its high nutritional value is attributable to its richness in bioactive compounds, particularly lycopene, polyphenols, vitamins and dietary fiber, known for their antioxidant effects and protection against chronic diseases.[5] Despite its economic and nutritional importance, tomato processing, which handles over 180 million

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tons of product, generates a volume of 4–10 million metric tonnes of wasted biomass globally each year.[6] Such waste volumes not only entail a logistical and economic burden for disposal but also have a negative environmental impact.

The disposal of food waste, such as pulp, skins, and seeds, from the agri-food sector in landfills or incinerators is expensive.[7] Furthermore, common approaches to food waste management often rely on either incinerating the waste or leaving it to decompose in fields, which results in significant air pollution and contamination of soil, water, and food resources.[8] Indeed, food waste drives climate change, generating approximately 4.4 billion tonnes of CO_2 equivalent each year, which accounts for about 8% of total anthropogenic greenhouse gas emissions.[9] Contrary to the perception of "waste", tomato peel and seeds are an extremely valuable by-product. While peels are tissues that accumulate high concentrations of lycopene, beta-carotene, and fiber, seeds are a rich source of proteins and healthy oils.[10] These compounds could be employed as functional substances in the formulation of various food products and utilized in cosmetic and pharmaceutical applications.[11]

Within the circular bio-economy framework, the food system cannot achieve sustainability without moving from a conventional linear model of production, consumption, and disposal to a circular, regenerative one,[12] based on the '3R' principle of reduce-reuse-recycle.[13] A 'bio-economy' can be defined as the "production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, bio-based products and bioenergy.[14] In this context, the upcycling of this industrial waste becomes a primary objective of food research.[15] This approach is one of several strategies within the circular bio-economy framework that can be applied to food waste management.[16] It enables the valorization of waste streams by converting them into higher-value products or ingredients,[17,18] thereby contributing to food chain sustainability.[19] The upcycling of food waste represents a strategic approach to alleviating the environmental burdens and the effects of climate change resulting from inefficient disposal of food residues.[20] However, it also poses several challenges,[21] including consumer acceptance and perception, technological limitations, government regulations, labeling requirements, and commercial scalability of various upcycling methods.[22–25] Despite these challenges, Moshtaghian *et al.*[21] emphasized the importance of incorporating food waste upcycling into the waste management hierarchy.

Therefore, this study aims to characterize the integration of tomato peels and seeds (TPSs) in pasta and gnocchi to develop food with increased nutritional benefits, while simultaneously promoting the sustainability and efficiency of the production process through the upcycling of agro-industrial by-products in a circular economy model. From a technological and sustainability perspective, peel and seeds are generated as a single by-product stream during tomato processing and are typically not separated at an industrial level. Therefore, their combined use better reflects a realistic and scalable valorization strategy, aligned with circular economy principles. From a compositional point of view, both fractions contribute valuable compounds and are expected to provide a more balanced enrichment of the final product, both nutritionally and functionally. To achieve the aim of the study, beyond sensory analysis, nutritional properties (in terms of total phenols, total flavonoids, antioxidant activity and total dietary fiber) and environmental impact were estimated. Finally, the Global Quality Index (GQI) integrated sensory, nutritional, and environmental aspects to demonstrate that all fortified formulations achieved a positive balance, to better compare pasta and gnocchi and demonstrate which product can show greater suitability for TPS incorporation.

2 Materials and methods

2.1 Raw materials

Tomato (cv. Taylor) peels and seeds (TPSs) were provided by the local farm Rosso Gargano (41°24′N latitude and 15°33′E longitude, Foggia, Italy) during the summer tomato processing. By-products contained around 85 g/100 g moisture. To stabilize and transform the by-products into a new ingredient, TPSs were dehydrated in a conventional dryer (PF-SICCO80PRO, SICCO TECH, Campobasso, Italy) using forced convection at atmospheric pressure, setting the temperature at 50 °C and the relative humidity at 5%. As reported by Lordi *et al.*[26] drying kinetics were obtained by measuring the loss of water during time. After drying, TPSs were milled using a lab grinder to obtain particle powder with a size lower than 500 μm.

2.2 Fresh pasta preparation

Four formulations of pasta were prepared: control pasta (ctrl) and pasta enriched with different concentrations of TPSs (19%, 21% and 23% w/w). The three formulations were designed using very close concentrations of TPSs because the goal of the study was to maximize the enrichment level while still retaining acceptable sensory quality. In particular, the selected concentrations represent the highest levels of added ingredients that ensured an overall acceptability score of at least 5 on a 9-point scale. To prepare control pasta, durum wheat semolina, water and fresh pasteurized eggs were adopted as ingredients. For pasta fortification, the three previous ingredients were partially substituted by TPSs. In these formulations carboxymethyl cellulose (CMC, 0.2%) was also added, being effective in improving the pasta structure. Semolina and eggs were purchased from a local market (Foggia, Italy). CMC was provided by Gioia Group srl (Torino, Italy). Some of the CMC solution was mixed with semolina flour and pasteurized eggs, while the rest was used to hydrate the TPS powder. The dough was prepared by mixing the ingredients and a final moisture content of approximately 30–32% was reached for about 7 min. The dough was then processed using a laboratory-scale pasta extruder (Monferrina, Torino, Italy). Extrusion was carried out under the following conditions: single-screw pasta extruder; barrel temperature maintained at 35–45 °C (to avoid thermal degradation of bioactive compounds); a screw speed of approximately 25–30 rpm; a bronze die (for troccoli shape) and ∼80–120 bar (depending on formulation) as extrusion pressure. After extrusion, the pasta was cut to the desired length (20 cm).

Table 1 Formulations of fresh pasta, with and without TPS powder as mass fractions

Ingredients	Ctrl	Pasta-L	Pasta-M	Pasta-H
Semolina	0.6900	0.530	0.5227	0.5109
Water	0.1800	0.1396	0.1363	0.1333
Fresh pasteurized eggs	0.1300	0.1008	0.0985	0.0963
TPS powder	—	0.1473	0.1591	0.1703
Water to hydrate TPS	—	0.0769	0.0830	0.0888
CMC	—	0.0004	0.0004	0.0004

Troccoli are a traditional Italian fresh pasta, like spaghetti but thicker and with a rough surface, which makes it particularly suitable for evaluating texture and sauce adhesion. The 3 fortified pasta samples were indicated as pasta-L, pasta-M and pasta-H to indicate low, medium and high TPS mass fractions. All the pasta formulations are reported in Table 1.

2.3 Fresh gnocchi preparation

For the gnocchi, 4 formulations were prepared too: a ctrl sample and 3 samples fortified with different concentrations of TPSs. A preliminary study was carried out to choose the 3 best formulations with the most TPS concentration while still retaining acceptable sensory quality (at least 5 on a 9-point scale). The following ingredients were used: water, potato flakes, wheat flour, potato starch, salt, lactic acid, sorbic acid, safflower, TPS powder and CMC (Table 2). To produce fortified samples, a proper weight of CMC was dissolved in water; when it was completely dissolved, the mixture was added to the boiler of a gnocchi machine (Condor, Italy) until it reached 130 °C. Once this temperature was reached, the heat was turned off, and all the other ingredients were added. The mixture was blended for 15 min without further heating. All control and fortified doughs were then manually shaped and formed into individual gnocchi pieces. Table 2 shows the respective formulations of all samples expressed in mass fractions. The fortified gnocchi samples were indicated as gnocchi-L, gnocchi-M and gnocchi-H to indicate the low, medium and high TPS mass fractions.

2.4 Sensory analyses of pasta and gnocchi

All fresh pasta and gnocchi samples were subjected to a sensory evaluation using quantitative descriptive analysis (QDA) and quality grading, abundantly adopted in the literature.[27,28] The panelists were asked to evaluate specific attributes and provide the overall liking score. The panel was composed of seven trained panelists (all females) with ages between 35 and 48 years, Researchers of the Food Department with high experience in sensory evaluation of food products. Panelists underwent two days of training sessions (1 session per day; 2 h per session) to establish specific sensory attributes and ensure result repeatability. During this phase, they were familiarized with the product category, the evaluation criteria, and the use of the scale. Reference samples were also discussed to align perception and improve consistency in scoring. The sensory evaluation was carried out on raw and cooked samples of troccoli and gnocchi. Each panelist evaluated approximately 100 g

Table 2 Formulations of gnocchi, with and without TPS powder as mass fractions

Ingredients	Ctrl	Gnocchi-L	Gnocchi-M	Gnocchi-H
Water	0.5741	0.4154	0.3948	0.4069
Potato flakes	0.0632	0.0457	0.0434	0.0448
Wheat flour	0.2584	0.1869	0.1777	0.1831
Potato starch	0.0919	0.0665	0.0632	0.0651
Salt	0.0072	0.0052	0.0049	0.0051
Lactic acid	0.0043	0.0031	0.0031	0.0031
Sorbic acid	0.0007	0.0005	0.0005	0.0005
Safflower	0.0003	0.0002	0.0002	0.0002
TPS powder	—	0.1256	0.1421	0.1465
Water to hydrate TPS	—	0.1483	0.1678	0.1424
CMC	—	0.0025	0.0024	0.0024

of cooked and uncooked samples, which is a typical portion size for pasta and gnocchi sensory testing, ensuring sufficient exposure without causing fatigue. Troccoli were cooked in boiling water (100 °C) for 9 min and 30 s, while gnocchi were cooked in boiling water (100 °C) for 2 min. These cooking times were selected based on preliminary tests to ensure optimal texture and typical consumption conditions for each product. Samples were served warm, immediately after cooking, with a controlled time interval of about 2–3 minutes to ensure uniformity. Temperature was monitored to maintain consistent serving conditions. Sensory evaluations were conducted in a controlled environment at approximately 22 ± 2 °C under neutral, uniform lighting to avoid any visual bias and ensure optimal assessment conditions. The raw samples were evaluated immediately after production, within 1 hour, to avoid any alterations. With regard to attributes, for pasta samples, the panelists were asked to indicate color, odor, homogeneity, appearance and breaking resistance of raw troccoli and odor, color, elasticity, bulkiness, stickiness, firmness, grittiness and taste of cooked troccoli. An overall quality of both raw and cooked samples was also considered an integrated evaluation to take into account the panelists' perception of the main individual attributes. The quality parameters for raw gnocchi were odor, color, appearance-homogeneity, breaking resistance and overall quality while odor, color, stickiness, grittiness, taste and overall quality are quality parameters for cooked gnocchi. Each attribute included in the QDA profile was accompanied by a precise, operational definition so that panelists clearly understood the sensory characteristics being measured. A 9-point scale was used for the assessment of each specific sensory attribute and for the overall quality (1 = lowest score; 9 = highest score; 5 = threshold for acceptability). The samples were presented randomly to each panelist with a 3-digit code. Water was used to clean the mouth for the sample taste. The assessment was carried out in two single sessions, one for pasta and another for gnocchi, during which each panelist evaluated four samples. Because the number of samples was limited and the sensory attributes were not overly demanding, sensory fatigue was minimal and did not affect the panelists' performance. Troccoli and gnocchi were prepared with food-grade ingredients and according to good manufacturing practices.

All food handling and preparation adhered to the fundamental principles of EU food legislation. All samples were prepared, handled, and cooked in a dedicated food preparation laboratory and were subject to rigorous safety checks. Each sample was accompanied by a clear ingredient list that indicated the presence of all major allergens. Raw materials and preparation steps were traceable to ensure food integrity. Considering that there were no risks associated for panelists who judged the samples, this experiment did not require Ethics Committee approval. An appropriate protocol was implemented to safeguard participant rights and privacy including securing informed verbal consent, ensuring the voluntary nature of participation (*i.e.*, no coercion and the ability to withdraw at any time), providing full disclosure of study requirements, and guaranteeing the confidentiality of collected data. It is also worth considering that before accepting to participate, each panelist declared the general state of health and any known food allergies or intolerances. Pregnant individuals are excluded from participation to minimize potential risks.

2.5 TPC, TFC and antioxidant activity of pasta and gnocchi

The following chemical reagents were used to determine the content of total phenols (TPC), flavonoids (TFC) and antioxidant activity (by ABTS and FRAP methods): Folin–Ciocalteu reagent, gallic acid monohydrate, anhydrous sodium carbonate, methanol, hydrochloric acid, 2,2-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS), potassium persulfate, Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid), aluminum chloride, sodium nitrite, sodium hydroxide solution and quercetin, supplied by Sigma Aldrich (Milan, Italy). All reagents were of analytical grade. For the chemical analyses, the extraction from pasta and gnocchi samples was performed as described by La Gatta *et al.*[29] with slight modifications. Initially, all the samples were dried on a ventilated stove (BINDER GmbH, Tuttlingen, Germany) at 35 °C and milled to obtain a powder. An amount of 2 g of each dried sample was mixed with 20 mL of acidified methanol (80% MeOH in H_2O acidified with 1% HCl). The mixtures were shaken at room temperature in the dark for 2 h at 3000 rpm (HS 260 BASIC, IKA, Staufen, Germany) and centrifuged at 4 °C for 10 min at 10.000 rpm (5804R, Eppendorf, Milan, Italy). Then, the supernatant was collected and filtered (PTFE, 0.45 μm) prior to the analytical determinations. All the extractions were made in triplicate, with appropriate dilutions. The Folin–Ciocalteu method, as described by Panza *et al.*,[30] was used for TPC, expressed as milligrams of gallic acid equivalents (GAE) per g of dry weight (dw), according to a calibration curve (3.12–100 mg L^{-1}; $R^2 = 0.999$). The aluminum chloride colorimetric method, as described by Panza *et al.*,[31] was used for TFC, expressed in milligrams of quercetin equivalent (QE) per g of dry weight (dw), according to a calibration curve (6.25–400 mg L^{-1}; $R^2 = 0.995$). The ABTS method, as described by Cedola *et al.*[32] and the FRAP method, as described by Marinelli *et al.*[33] were used for the antioxidant activity. ABTS values were expressed as milligrams of Trolox equivalents per g of dry weight (dw), according to a calibration curve at concentrations between 12.5 and 500 mg L^{-1} ($R^2 = 0.990$); FRAP values were expressed as μmol of ferrous equivalent Fe(II) per g of dry weight (dw), according to a calibration curve at concentrations between 0.8 and 0.1 mmol L^{-1} ($R^2 = 0.993$). All the analyses were carried out in triplicate.

2.6 Fiber content

Total dietary fibre (TDF) content was assessed in both control and fortified samples by NIRO SRL laboratory (Campobasso, Italy), according to the AOAC Official Method,[34] and expressed in g/100 g.

2.7 Environmental impact analysis

The environmental evaluation was carried out using Life Cycle Assessment (LCA), a methodology employed to measure the environmental impacts and benefits associated with a product or service throughout its entire life cycle, from raw material extraction to disposal.[35] At the international level, it is regulated by the ISO 14040 series of standards, which structure an LCA study into four phases: definition of the goal and scope, inventory analysis, impact assessment, and interpretation of results.[36,37] In this study, tomato peels and seeds are considered generic biowaste, and the processes related to their production and industrial processing, along with the associated environmental impacts, were excluded from the analysis. This approach treats biowaste as "burden-free", assuming no impacts from the upstream stages, and is justified as these impacts are identical across all recycling scenarios examined.[38] In the first phase of the LCA, the definition of the functional unit (FU) is a decisive step as it will influence the outcome.[39] It describes the primary function of a product[40] to which all inputs and outputs refer.[41] In this case, the FU was defined as 1 kg of product (pasta and gnocchi). As the employed database lacked data for certain ingredients, the specific emission factors for these components were derived from the sources listed below. The production data for semolina and its associated carbon footprint were obtained from the Environmental Product Declaration,[42] while those for eggs were sourced from Leinonen *et al.*[43] Citric acid was used as a proxy for sorbic acid, as the latter was not available in the considered dataset. Furthermore, it was assumed that producing 1 kg of potato flakes requires 5 kg of potatoes, as reported in the study by Hu *et al.*[44] The energy required for converting potatoes into potato flakes was taken from the report by Walker *et al.*[45] During the Life Cycle Inventory (LCI) phase, primary data were collected through direct measurements conducted during experimental activities at the University of Foggia. These data included both the energy consumption associated with the drying and milling of the by-products and the composition, in terms of ingredients, of the pasta and gnocchi produced. The inventory data are provided in Tables S7 and S8. In the Life Cycle Impact Assessment (LCIA) phase, a quantitative evaluation was carried out to assess the carbon footprint of the scenarios considered. In this study, the potential impact within the chosen category was estimated using the "CML-IA baseline v. 3.07" method, implemented through SimaPro software v. 10.3.0. The environmental impact category considered was the 100-year Global Warming Potential (GWP100), expressed in kilograms of CO_2 equivalent (kg CO_2 eq.). In the context of life cycle assessment, the results associated with this impact category are generally referred to as the 'carbon footprint'.[46]

2.8 Calculation of the global quality index

The procedure suggested by Lordi *et al.*[26] was used to calculate the Global Quality Index (GQI). The positive aspects associated with fortification (Positive Quality Index, PQI) are related to the increased nutritional quality (such as environmental impact, total dietary fiber, FRAP, and ABTS), while the negative aspect (Negative Quality Index, NQI) associated with fortification was the sensory quality (score of the overall quality).

The normalization of the quality indices (PQI and NQI) was made according to the following expressions, as the percentage difference between the sample fortified with TPSs and the control:

$$\text{Normalized environmental impact (N\_EI)} = \frac{\mathrm{PQI}_{\mathrm{EI}}^{\mathrm{CTR}} - \mathrm{PQI}_{\mathrm{EI}}^{\mathrm{Act}}}{\mathrm{PQI}_{\mathrm{EI}}^{\mathrm{CTR}}} \times 100 \quad (1)$$

$$\text{Normalized totale dietary fiber (N\_TDF)} = \frac{\mathrm{PQI}_{\mathrm{TDF}}^{\mathrm{Act}} - \mathrm{PQI}_{\mathrm{TDF}}^{\mathrm{CTR}}}{\mathrm{PQI}_{\mathrm{TDF}}^{\mathrm{CTR}}} \times 100 \quad (2)$$

$$\text{Normalized FRAP (N\_FRAP)} = \frac{\mathrm{PQI}_{\mathrm{FRAP}}^{\mathrm{Act}} - \mathrm{PQI}_{\mathrm{FRAP}}^{\mathrm{CTR}}}{\mathrm{PQI}_{\mathrm{FRAP}}^{\mathrm{CTR}}} \times 100 \quad (3)$$

$$\text{Normalized ABTS (N\_ABTS)} = \frac{\mathrm{PQI}_{\mathrm{ABTS}}^{\mathrm{Act}} - \mathrm{PQI}_{\mathrm{ABTS}}^{\mathrm{CTR}}}{\mathrm{PQI}_{\mathrm{ABTS}}^{\mathrm{CTR}}} \times 100 \quad (4)$$

$$\text{Normalized sensory quality (N\_SQ)} = \frac{\mathrm{NQI}_{\mathrm{SQ}}^{\mathrm{CTR}} - \mathrm{NQI}_{\mathrm{SQ}}^{\mathrm{Act}}}{\mathrm{NQI}_{\mathrm{SQ}}^{\mathrm{CTR}}} \times 100 \quad (5)$$

where $\mathrm{PQI}_{\mathrm{EI}}^{\mathrm{CTR}}$ is the positive quality index of the control sample related to the environmental impact, $\mathrm{PQI}_{\mathrm{EI}}^{\mathrm{Act}}$ is the positive quality index of the active sample related to the environmental impact, $\mathrm{PQI}_{\mathrm{TDF}}^{\mathrm{CTR}}$ is the positive quality index of the control sample related to the total dietary fiber, $\mathrm{PQI}_{\mathrm{TDF}}^{\mathrm{Act}}$ is the positive quality index of the active sample related to the total dietary fiber, $\mathrm{PQI}_{\mathrm{FRAP}}^{\mathrm{CTR}}$ is the positive quality index of the control sample related to FRAP, $\mathrm{PQI}_{\mathrm{FRAP}}^{\mathrm{Act}}$ is the positive quality index of the active sample related to FRAP, $\mathrm{PQI}_{\mathrm{ABTS}}^{\mathrm{CTR}}$ is the positive quality index of the control sample related to ABTS, $\mathrm{PQI}_{\mathrm{ABTS}}^{\mathrm{Act}}$ is the positive quality index of the active sample related to ABTS, $\mathrm{NQI}_{\mathrm{SQ}}^{\mathrm{CTR}}$ is the negative quality index of the control sample related to the sensory quality, and $\mathrm{NQI}_{\mathrm{SQ}}^{\mathrm{Act}}$ is the negative quality index of the active sample related to the sensory quality.

The GQI was defined according to the following expression, considering with equal importance the environmental impact and the nutritional quality in terms of fiber content, ABTS and FRAP values:

$$\mathrm{GQI} = \frac{\frac{1}{2}\left(\frac{\mathrm{PQI}_{\mathrm{EI}}^{\mathrm{CTR}} - \mathrm{PQI}_{\mathrm{EI}}^{\mathrm{Act}}}{\mathrm{PQI}_{\mathrm{EI}}^{\mathrm{CTR}}}\right) + \frac{1}{2}\left(\frac{\frac{\mathrm{PQI}_{\mathrm{TDF}}^{\mathrm{Act}} - \mathrm{PQI}_{\mathrm{TDF}}^{\mathrm{CTR}}}{\mathrm{PQI}_{\mathrm{TDF}}^{\mathrm{CTR}}} + \frac{\mathrm{PQI}_{\mathrm{FRAP}}^{\mathrm{Act}} - \mathrm{PQI}_{\mathrm{FRAP}}^{\mathrm{CTR}}}{\mathrm{PQI}_{\mathrm{FRAP}}^{\mathrm{CTR}}} + \frac{\mathrm{PQI}_{\mathrm{ABTS}}^{\mathrm{Act}} - \mathrm{PQI}_{\mathrm{ABTS}}^{\mathrm{CTR}}}{\mathrm{PQI}_{\mathrm{ABTS}}^{\mathrm{CTR}}}}{3}\right)}{\frac{\mathrm{NQI}_{\mathrm{SQ}}^{\mathrm{CTR}} - \mathrm{NQI}_{\mathrm{SQ}}^{\mathrm{Act}}}{\mathrm{NQI}_{\mathrm{SQ}}^{\mathrm{CTR}}}} \quad (6)$$

2.9 Statistical analysis

The experimental data from sensory analysis of raw and cooked products, ABTS and FRAP assays and total dietary fiber were compared by a one-way analysis of variance. Mean data were separated using Tukey's HSD, with the option of homogeneous groups ($p < 0.05$). To evaluate statistically significant differences among samples, JMP 18 for Windows (JMP Statistical Discovery LLC 920 SAS Campus Drive, Cary, NC 27513) was used.

3 Results and discussion

Sensory quality and nutritional properties were first evaluated in pasta and gnocchi to identify both the benefits and potential limitations associated with TPS fortification. Subsequently, the LCA approach was conducted to verify whether the incorporation of recycled TPSs in staple foods could also provide environmental advantages. A comprehensive evaluation, integrating sensory performance, nutritional enhancement, and environmental impact, was necessary to reliably assess the overall effectiveness of TPS upcycling and to determine the most suitable formulation. For this reason, after discussing sensory results, nutritional improvements, and environmental outcomes, a final section was devoted to the Global Quality Index (GQI), which enabled a combined and more robust interpretation of all dimensions.

3.1 Sensory quality of pasta and gnocchi

The complete sensory dataset, including the statistical analysis (ANOVA), is provided in the SI to ensure transparency and allow readers to access detailed numerical results. From these data it is possible to infer that sensory evaluation of uncooked fortified pasta and the corresponding control indicated that all samples were well accepted by the panelists, with no defects in odor, color, or appearance/homogeneity (TS1). Sensory scores for fortified samples did not differ significantly from those of the control ($p > 0.05$). Breaking resistance was the attribute most affected by the inclusion of TPSs. This effect is expected, as TPSs interfere with the formation of the gluten network because these materials are rich in insoluble fiber, which interferes with continuous network formation.[47,48] This disruption reduces the structural cohesion of the dough, making the pasta more brittle and prone to fracture. Additionally, the presence of coarse particles can create microstructural discontinuities that act as weak points under mechanical stress. Consequently, higher by-product concentrations yield a weaker gluten network and, in turn, a reduced sensory perception of breaking resistance. A similar trend was observed in the sensory analysis of cooked pasta samples (TS2). Only a limited number of sensory attributes were consistently influenced by the presence of TPSs, but these effects were sufficient to have a noticeable impact on overall quality. Increasing TPS levels caused a reduction in elasticity, grittiness, and taste. This is due to the high fiber content of TPSs that disrupted the gluten network, reducing dough cohesiveness and flexibility. At the same time, the presence of insoluble particles contributed to a perceptible grittiness, negatively affecting mouthfeel. These structural and textural changes also influenced taste perception, as the altered matrix can modify flavor release and introduce slight off-notes, ultimately resulting in a decrease in overall sensory quality compared with the control. Comparable findings were reported in studies examining pasta enriched with other by-products, such as asparagus pruning waste,[49] grape pomace and olive pomace (pâté),[50] celery root and sugar beet by-products.[51]

The overall quality of the uncooked pasta was significantly higher than that of the cooked samples. As a result, the sensory evaluation of cooked pasta became the limiting factor in assessing the suitability of the product for TPS enrichment, since cooking amplified the textural and sensory differences among formulations. This outcome advances the valorization of industrial by-products in the pasta sector, as previous studies reported major sensory defects at fortification levels above 15%,[47,52] whereas our results demonstrate that, with proper optimization, TPSs can be incorporated up to 23% while retaining acceptable sensory quality.

The sensory evaluation of uncooked fortified and control gnocchi (TS3) showed minimal differences, only occasionally reaching statistical significance ($p < 0.05$). In contrast, for cooked samples, grittiness and taste were the attributes most affected by TPS addition (TS4) due to both the composition of TPSs and the structure of the product. The high content of insoluble fiber and residual particles from TPSs was less effectively embedded in the soft, low-gluten matrix of gnocchi, making these particles more perceptible during mastication and thus increasing grittiness.[53] At the same time, this matrix allowed a faster and less controlled release of compounds from TPSs, which can intensify vegetal or slightly bitter notes, leading to a more pronounced impact on taste compared to more structured products like pasta.[54] Stickiness was also influenced, although to a lesser extent. Stickiness reflects the viscosity experienced during consumption and it is related to the amount of starch granules released from the matrix into the cooking water and deposited onto the product surface.[55] Consistent with observations made by Krishnan *et al.*,[48] adhesiveness was higher in the control sample and lower in the fortified gnocchi because its matrix, mainly composed of starch, undergoes greater gelatinization during cooking, leading to the formation of a more cohesive and stickier surface. In contrast, the addition of TPSs, rich in insoluble fiber, diluted the starch fraction and interfered with starch swelling and gel formation. As a result, the fortified gnocchi exhibit a less cohesive surface structure, leading to lower adhesiveness values. As observed for pasta, the overall quality of cooked gnocchi was always lower than that of the uncooked samples. Consequently, overall quality of cooked gnocchi was used as the quantitative measure of TPS impact on gnocchi sensory performance.

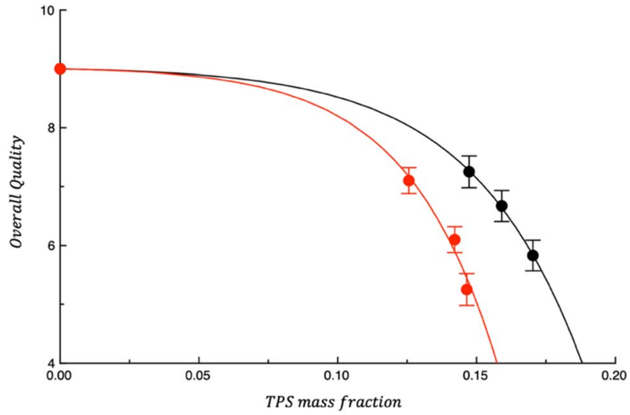

Fig. 1 Overall quality of cooked pasta and gnocchi samples as a function of the TPS mass fraction. ● gnocchi, ● pasta, —— gnocchi, and —— pasta. The curves shown in the figure are intended solely to highlight the trend of the data.

Fig. 1 reports the overall quality of pasta and gnocchi as a function of the TPS mass fraction. It allows a clear and more immediate comparison among samples. It was designed to highlight, in a straightforward and intuitive way, the differences in overall acceptability not only across the different concentrations of TPSs, but also between troccoli and gnocchi. As previously described, TPS addition reduces the sensory quality of both matrices. A progressive decline in sensory quality with increasing by-product concentration is expected. At equivalent TPS mass fractions, the sensory quality of pasta is consistently higher than that of gnocchi, indicating a greater tolerance of pasta to TPS incorporation. This difference is likely attributable to the softer texture of gnocchi, which may enhance the perception of TPS granules. Notably, grittiness was among the sensory attributes exerting the strongest influence on overall product quality.

3.2 Nutritional quality of pasta and gnocchi

Table 3 presents the antioxidant activity determined by the ABTS and FRAP assays and the total dietary fiber (TDF) content,

Table 3 Antioxidant activity (by ABTS and FRAP) and Total Dietary Fiber (TDF) of pasta and gnocchi, with and without TPSs[a]

Sample	ABTS [mg Trolox per g dw]	FRAP [μmol Fe(II) per g dw]	TDF [g/100 g]
CTRL pasta	$1.71 \pm 0.08^{a,b,c}$	3.80 ± 0.076^{d}	3.4 ± 0.205^{c}
Pasta-L	$2.02 \pm 0.08^{a,b}$	4.91 ± 0.131^{b}	$13.7 \pm 0.796^{a,b}$
Pasta-M	2.33 ± 0.19^{a}	5.34 ± 0.123^{a}	$14.6 \pm 0.847^{a,b}$
Pasta-H	2.44 ± 0.16^{a}	5.37 ± 0.134^{a}	15.7 ± 0.911^{a}
CTRL gnocchi	0.96 ± 0.20^{c}	3.21 ± 0.095^{e}	2.3 ± 0.142^{c}
Gnocchi-L	$1.43 \pm 0.40^{b,c}$	4.33 ± 0.186^{c}	12.9 ± 0.750^{b}
Gnocchi-M	$1.49 \pm 0.42^{b,c}$	$4.59 \pm 0.104^{b,c}$	$14.4 \pm 0.836^{a,b}$
Gnocchi-H	$1.57 \pm 0.07^{b,c}$	5.38 ± 0.201^{a}	$14.8 \pm 0.859^{a,b}$

[a] Data are reported as means ± SD. Data in each column with different superscript letters are statistically different ($p < 0.05$).

for both fortified and unfortified pasta and gnocchi samples. Overall, an increase in antioxidant activity was observed in the fortified samples compared with their respective controls. This increase is mainly attributable to the incorporation of TPSs that are naturally rich in bioactive compounds such as polyphenols, flavonoids, and carotenoids. These compounds possess strong radical-scavenging properties and significantly contribute to the overall antioxidant capacity measured by assays such as ABTS and FRAP.[5] In contrast, the control samples, based primarily on refined ingredients, contain lower levels of these compounds. Furthermore, the data in Table 3 show that, for each food matrix, antioxidant activity increased as the concentration of TPSs increased. In some cases, the absence of statistically significant differences can be attributed to the limited TPS concentrations employed, since higher levels than those used in this study have been associated with sensory defects. Fig. S1 provides a clear visualization of differences among samples in terms of antioxidant activity measured by both ABTS and FRAP. Our results are consistent with those of several studies in the literature reporting enhanced antioxidant activity depending on the type and amount of by-products incorporated into the formulation. Michalak-Majewska *et al.*[56] substituted semolina with onion skin powder in pasta at 2.5, 5 and 7.5 g/100 g levels. Fortification with onion skin resulted in a significant ($p < 0.05$) improvement in nutritional properties, which was demonstrated by an increase in the content of total phenolic compounds, flavonoid content and antioxidant activity (FRAP and DPPH).[56] Tolve *et al.*[57] also demonstrated that pasta prepared by replacing semolina with 0, 5, and 10 g/100 g of grape pomace significantly increased the total phenol content and the antioxidant activity, evaluated through ABTS and FRAP assays ($p < 0.05$).[57]

Regarding TDF both pasta and gnocchi exhibited a marked and statistically significant increase in the fortified formulations compared with their respective controls. Moreover, a clear dose–response relationship was observed, with TDF levels progressively increasing in proportion to the amount of TPSs added, confirming the effectiveness of the by-product as a fiber-enriching ingredient.[48,54]

Fig. S2 provides a clear comparison among samples in terms of fiber content because it reports TDF of pasta and gnocchi as a function of TPS concentration, highlighting slightly better results for fortified gnocchi.

Data reported in Tables S5 and S6 show that the polyphenol and flavonoid contents were also higher in fortified pasta and gnocchi samples than in their respective controls. As noted by Padalino *et al.*,[47] the observed increase in TPC and TFC was directly influenced by the level of TPS powder incorporated into

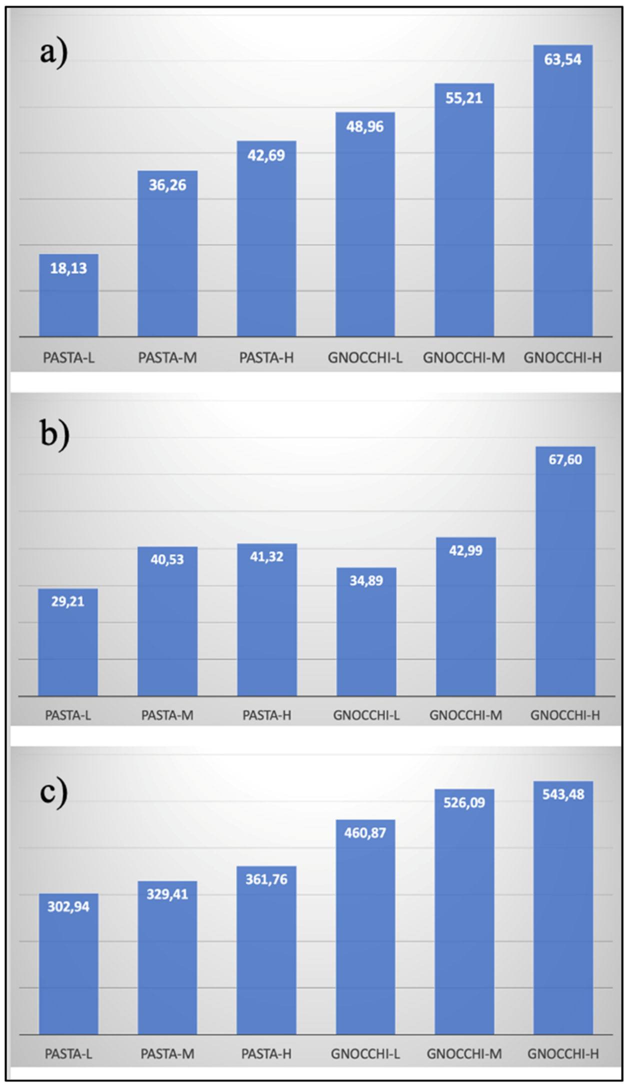

Fig. 2 Values of percentage normalized ABTS (a), percentage normalized FRAP (b) and percentage normalized TDF (c), calculated using eqn (2)–(4).

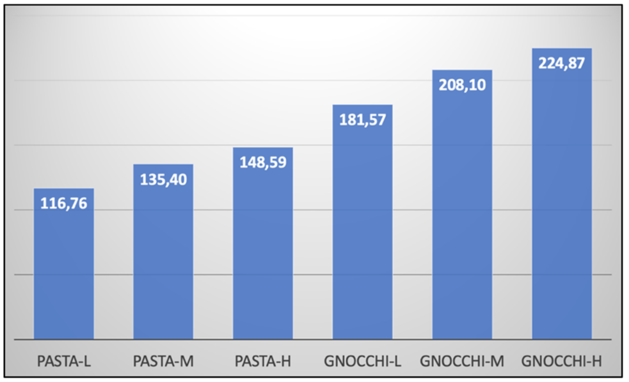

Fig. 3 Average of the three normalized nutritional indicators ABTS, FRAP and TDF.

the dough. In particular, higher inclusion rates resulted in a proportional enrichment of these bioactive compounds, highlighting a clear concentration-dependent effect and confirming the role of TPSs as an effective source of phenolics and flavonoids. Merlino *et al.*[54] likewise demonstrated that fortifying gnocchi with hemp seed flour, a valuable source of bioactive compounds, improves their nutritional profile.

Fig. 2 shows the percentage normalized values of ABTS, FRAP and TDF for pasta and gnocchi, calculated using eqn (2)–(4). Fig. 2a shows the percentage normalized values of ABTS (N_ABTS) for the fortified pasta and gnocchi samples. As can be seen, all fortified gnocchi samples exhibited a higher percentage increase in ABTS than that observed for the fortified pasta samples. In principle, two factors may influence these findings: the ABTS value of the control and by-product concentration. ABTS value of the gnocchi control was lower compared with that of pasta. Indeed, the TPS concentrations used in the gnocchi formulations were slightly lower than those employed for pasta (see Tables 1 and 2). Fig. 2b presents the percentage normalized values of FRAP (N_FRAP) of the fortified pasta and gnocchi samples. Again, gnocchi appear to be more suitable for TPS fortification, as their N_FRAP values are slightly higher than those of pasta. As before, this trend is related to the FRAP values of the two controls, with gnocchi displaying a slightly lower value than pasta. Fig. 2c shows the percentage normalized values of TDF (N_TDF) for the fortified gnocchi and pasta samples. As observed for the previous nutritional indicators, the fortified gnocchi samples displayed a greater percentage increase in TDF than the corresponding pasta samples. As before the primary factor underlying this result is the lower fiber content of the gnocchi control compared with the troccoli control.

Fig. 3 shows the average of the three normalized nutritional indicators (*i.e.*, N_ABTS, N_FRAP, and N_TDF). Based on normalized nutritional quality, TPSs are more effective at fortifying gnocchi than pasta. Indeed, across all the previous normalized nutritional indicators, gnocchi consistently exhibited higher values than the corresponding pasta samples.

3.3 Environmental impact assessment

Fig. 4 illustrates that the carbon footprint of the control pasta formulation (1.08 kg CO_2 eq.) is slightly higher than that of the enriched formulations, namely pasta-L, pasta-M, and pasta-H, which show values of 1.04, 1.03, and 1.03 kg CO_2 eq., respectively. The incorporation of by-products into the novel pasta formulations reduces the required amounts of conventional ingredients, such as semolina and egg, thereby lowering the associated carbon footprint. However, the environmental benefit is counterbalanced by the electricity demand required for by-product processing (highlighted in yellow in the graph), which contributes substantially to the overall carbon footprint of the enriched formulations.

Fig. 5 shows the carbon footprint of all gnocchi formulations. The carbon footprint of the control formulation (0.68 kg CO_2 eq.) is comparable to that of the gnocchi-L formulation

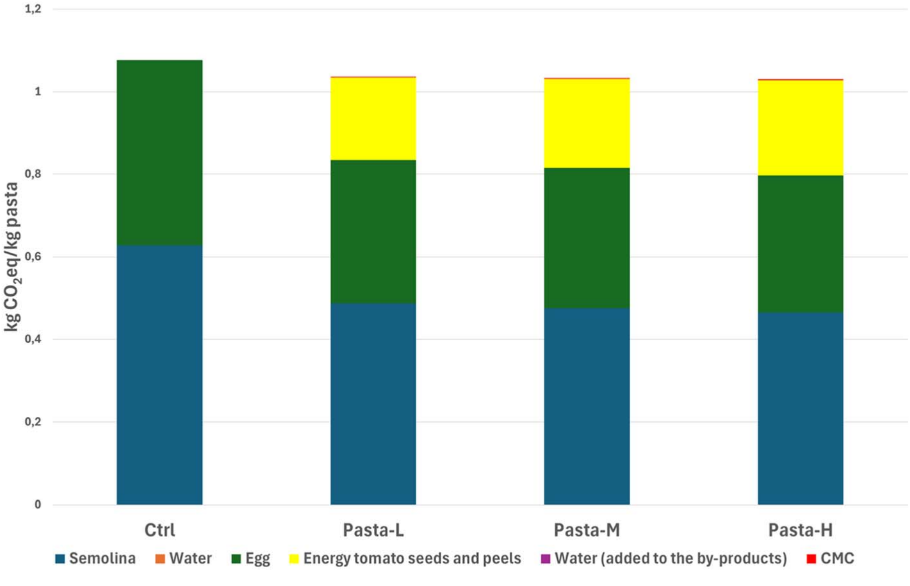

Fig. 4 Global warming potential expressed in kg of CO_2 eq. per kg of pasta. Each segment in the stacked bars represents the contribution of a specific ingredient. The control formulation shows slightly higher emissions than the fortified ones.

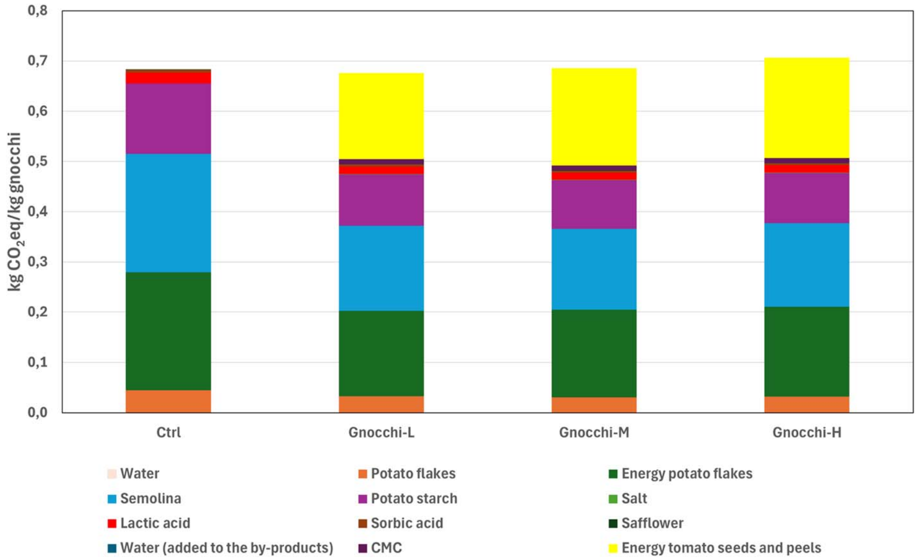

Fig. 5 Global warming potential expressed in kg of CO_2 eq. per kg of gnocchi. Each segment in the stacked bars represents the contribution of a specific ingredient. The control formulation shows lower emissions than the fortified ones.

(0.68 kg CO_2 eq., when rounded to two decimal places), although minor differences are observed in the unrounded values. In the latter, the reduction in conventional ingredients, such as semolina, potato starch, and potato flakes (including the energy demand associated with potato flake production), contributes to lower environmental impacts. However, these reductions are offset by the energy consumption associated with the recycling process, resulting in similar overall values. The gnocchi-M and gnocchi-H formulations exhibit slightly higher impacts (0.69 and 0.71 kg CO_2 eq., respectively), as the variations in ingredient composition, including by-products, are not sufficient to substantially alter the total carbon footprint.

A sensitivity analysis was performed to assess the influence of different electricity datasets on the GWP results. The baseline scenario was defined using the Italian medium voltage electricity mix (electricity, medium voltage IT), which also represents a modelling assumption of this study, intended to reflect a representative industrial electricity supply in Italy. Alternative scenarios considered variations in both geographical scope (Italy *vs.* Europe without Switzerland) and voltage levels (low, medium, and high voltage). The results indicate that GWP values are only marginally affected by the electricity dataset. Across all scenarios, variations range from 0% to approximately −4.8% compared to the baseline. The largest deviation occurs for low voltage electricity, whereas medium and high voltage datasets yield identical or nearly identical results. Differences between Italian and European electricity mixes are also limited, generally below 2%.

Overall, the sensitivity analysis confirms the robustness of the results with respect to electricity input assumptions. The observed variations in GWP are negligible (<5%), indicating that the study conclusions are not sensitive to the choice of the electricity dataset or voltage level. Importantly, the relative comparison among scenarios remains unchanged across all electricity configurations.

Fig. S3 (SI) reports the values of percentage normalized environmental impact calculated using eqn (1) and highlights that these values are >1, except for the samples gnocchi-M and gnocchi-H. In all fortified formulations considered, energy consumption contributed a non-negligible share to the carbon footprint. Recycling processes are not always environmentally advantageous, as they can be more energy-intensive than producing new materials.[58] In these cases, the energy required to dehydrate and mill the tomato by-products is associated with a similar carbon footprint to that of the ingredients they partially replace. In the report by Lordi *et al.*[26] tomato by-products were used to replace meat. Such a difference is mainly due to the ingredient replaced and its carbon footprint associated, with meat being one of the foods with the highest impact among various items. Therefore, the carbon footprint resulting from by-products valorization depends on several factors, including the amount and type of energy employed, the physicochemical properties of the incorporated by-products (particularly their water content, which determines the energy required for dehydration), and the type of traditional ingredient being replaced. Valorizing these by-products is important not only for the recovery of additional nutrients and bioactive compounds, but also for preventing the environmental emissions associated with the disposal of these materials traditionally classified as waste.[59] Therefore, it is essential to select a food waste valorization technology that takes into account the moisture content and the composition of the waste in order to avoid an energy-intensive process and ensure the production of products with high added value.[60]

3.4 Global quality index

Fig. 6 displays the average of the normalized environmental impact and the mean of the three normalized nutritional indicators reported in Fig. 3. Specifically, the values shown in the figure correspond to the numerator of eqn (6). From Fig. 6, it

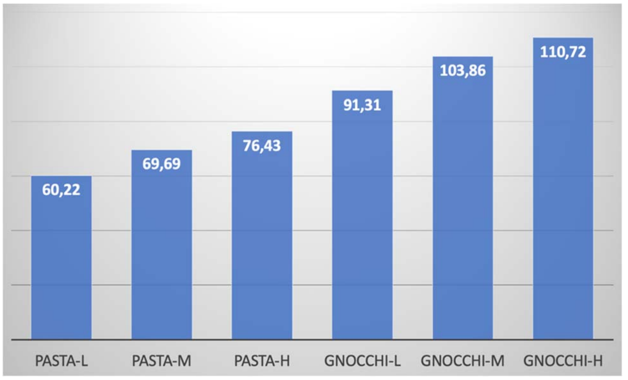

Fig. 6 Average between normalized values of environmental impact and nutritional quality. Values are the numerator of eqn (6).

can be observed that for both food matrices analyzed, the average of environmental impact and nutritional quality remains consistently positive, despite some N_EI values < 1 (Fig. S3). This suggests that the improvement in nutritional quality resulting from TPS fortification outweighed the associated increase in environmental impact. For both fortified pasta and gnocchi samples, a slight increase was observed as the by-product concentration increased. The data in Fig. 6 also indicate that the fortified gnocchi consistently exhibit higher values than the corresponding fortified pasta samples. This outcome can be attributed to the systematically higher values of the normalized nutritional indicators observed for the gnocchi compared with the pasta samples. It is not straightforward to compare these findings with similar studies in the literature, as the approach of simultaneously combining the nutritional benefits of fortification with its environmental impact remains relatively novel in this field. To date, no studies have specifically investigated pasta fortification while also assessing the environmental sustainability associated with the valorization of by-products. However, a previous study conducted by the same authors,[61] focusing on the use of artichoke and olive processing by-products, highlighted how the environmental impact can vary depending on the type of ingredient used, due to the energy consumption required for by-product processing. In that case, compared to the control sample (1.08 kg CO_2 eq.), lower carbon footprint values were observed for pasta fortified with olive pomace (0.96–0.98 kg CO_2 eq.), whereas higher values were reported for pasta enriched with artichoke by-products (1.53–1.62 kg CO_2 eq.).

Fig. 7 shows the N_SQ values calculated using eqn (5) for the fortified pasta and gnocchi samples. As illustrated in Fig. 7, gnocchi are more affected by the presence of TPSs, as they consistently exhibit lower N_SQ values than the corresponding fortified pasta sample. As previously discussed, compared to pasta, gnocchi have a softer, less cohesive matrix that is more sensitive to the incorporation of non-traditional ingredients such as TPSs. The addition of TPSs likely interferes with the starch network and moisture distribution, leading to changes in texture, such as increased stickiness or reduced firmness, which negatively impact sensory perception.[62] Moreover, the relatively mild flavor profile of gnocchi makes any off-flavors, color changes, or textural alterations introduced by TPSs more noticeable. For example, the addition of tomato powder above 9% also in bread negatively affected aroma and taste, despite the baking properties remaining comparable to those of the control sample.[63] In contrast, pasta typically has a firmer structure and a more resilient gluten network, which can better accommodate the inclusion of fortifying ingredients, thus preserving more acceptable sensory attributes. While cereal-based products often show sensory drawbacks following fortification, meat-based products may instead exhibit improvements in their sensory properties such as juiciness, texture, or flavor complexity and in some cases even contribute positively to color stability. Modzelewska-Kapitula & Wiek[64] observed that meat-based products enriched with TPSs were more acceptable than the control, owing to the distinctive flavor imparted by tomato by-products and the presence of lycopene, which acts as an effective red colorant, masking the typical greying caused by oxidation and improving visual appeal.

Fig. 8 shows the GQI values for the fortified pasta and gnocchi samples. As previously noted, the GQI represents the ratio between the expected benefits of TPS fortification and what is considered the primary disadvantage associated with fortification. A negative numerator indicates that the presumed benefits instead resulted in disadvantages, whereas a positive GQI value < 1 suggests that the disadvantages outweigh the

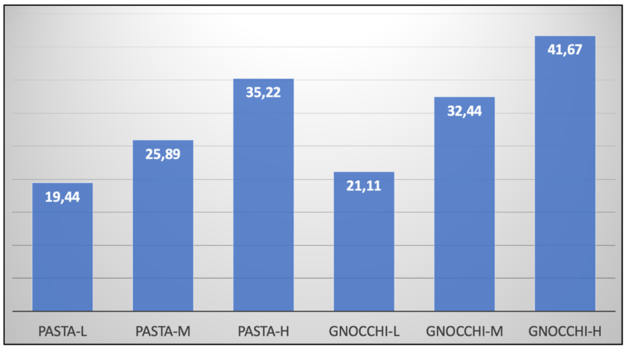

Fig. 7 Values of percentage normalized sensory quality calculated using eqn (5).

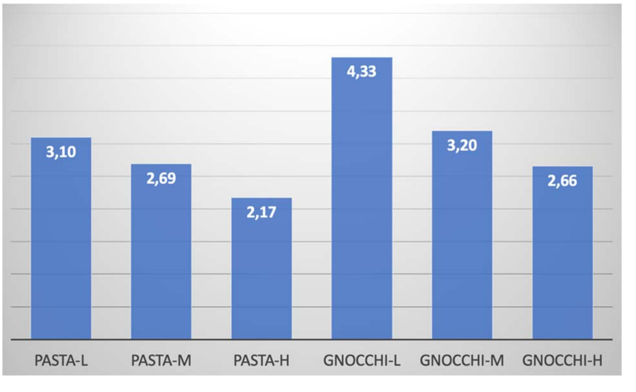

Fig. 8 Values of GQI calculated using eqn (6).

advantages. Conversely, GQI values > 1 indicate that the expected benefits are indeed achieved and surpass the associated drawbacks. For a more detailed explanation of the GQI, readers are referred to the work of Lordi *et al.*,[26] in which the index was introduced for the first time. Data in Fig. 8 show that all fortified samples exhibited a GQI value greater than 1, confirming that TPSs are effective in fortifying both pasta and gnocchi. For both food matrices examined, a progressive decline in the GQI was observed with increasing TPS concentration, indicating that as the level of by-product incorporation increases, the associated drawbacks tend to increase more rapidly than the corresponding benefits. This trend suggests the existence of a threshold beyond which further enrichment no longer provides a balanced improvement but instead leads to a net reduction in overall product quality. Nevertheless, when comparing the two matrices, gnocchi with the lowest TPS concentration appear to be more suitable for TPS fortification. Despite the general decrease in the GQI at higher inclusion levels, gnocchi consistently show higher values than the corresponding pasta samples. This indicates a better overall balance between nutritional enhancement, environmental impact, and sensory attributes in gnocchi, suggesting that their formulation is more capable of accommodating TPSs than pasta.

4 Conclusion

This study demonstrates that despite certain sensory drawbacks emerging with higher TPS concentrations, the overall balance of findings highlights the feasibility and potential of integrating TPS by-products into staple foods. TPS enrichment significantly enhanced the nutritional profile of both pasta and gnocchi, showing consistent increases in antioxidant capacity, polyphenols, flavonoids, and total dietary fiber. Sensory evaluation indicated that while uncooked samples were generally well received, the cooked products showed more pronounced effects of TPS incorporation. Attributes such as grittiness, elasticity, and taste were particularly sensitive to by-product addition. The softer texture of gnocchi made them more susceptible to sensory alterations than pasta, highlighting the matrix-dependent nature of by-product integration. Nevertheless, even at the highest enrichment levels, sensory acceptability remained above threshold values, demonstrating that careful formulation and process optimization can mitigate quality losses. The environmental assessment highlighted a key trade-off. Although TPS supplementation decreases the demand for conventional raw materials and generates environmental benefits, the energy required for TPS drying and milling offsets these gains, resulting in carbon footprint values comparable to those of the control formulations. This reflects a wider challenge in food waste valorization: environmental benefits depend not only on the value of the recovered material but also on the efficiency of the recovery process. By integrating sensory, nutritional, and environmental data into the Global Quality Index (GQI), the study provides a holistic evaluation tool that clarifies the real advantages of fortification. All fortified samples achieved GQI values above 1, demonstrating that the nutritional gains outweigh the sensory penalties and environmental burdens. Moreover, gnocchi consistently exhibited higher GQI values than pasta, supporting their greater suitability for TPS incorporation, despite being more sensitive from a sensory perspective. This is attributed primarily to the larger relative nutritional gains in gnocchi compared to pasta.

The development of integrated strategies for the management and valorization of agri-food by-products represents a key element to maximize environmental benefits and promote the transition toward a sustainable circular bioeconomy. In the agri-food sector, these strategies transform waste into high-value products, reducing environmental impacts and optimizing resource use. Although previous studies, including ours, have explored aspects of by-product valorization, a comprehensive assessment of the potential benefits and impacts from multiple perspectives, such as sensory, nutritional, and environmental, remains limited. To address this gap and expand the field of research, future studies should analyze the potential benefits and impacts of by-product valorization from multiple perspectives. In addition, future research should focus on optimizing low-energy drying technologies, evaluating alternative carriers or processing conditions to improve sensory integration, and broadening the application of TPSs to other food matrices. A comprehensive understanding of consumer acceptance and market positioning will also be essential for real-world implementation.

Author contributions

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

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.

Abbreviations

CMC	Carboxymethyl cellulose
CTRL	Control
FU	Functional unit
GQI	Global quality index
GWP100	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NQI	Negative quality index
PQI	Positive quality index

TDF	Total dietary fibre
TPC	Total phenol content
TFC	Total flavonoid content
TPSs	Tomato seeds and peels

Data availability

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

Supplementary information (SI): Table S1. Sensory characteristics of raw pasta samples with and without TPS. Table S2. Sensory characteristics of cooked pasta samples with and without TPS. Table S3. Sensory characteristics of raw gnocchi samples with and without TPS. Table S4. Sensory characteristics of cooked gnocchi samples with and without TPS. Table S5. Total Polyphenol Content (TPC) and Total Flavonoid Content (TFC) of pasta samples with and without TPS. Table S6. Total Polyphenol Content (TPC) and Total Flavonoid Content (TFC) of gnocchi samples with and without TPS. Table S7. Ingredients (g/1 kg pasta) used for pasta preparation, along with the corresponding sources of environmental impact data. See DOI: https://doi.org/10.1039/d5fb00954e.

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