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Original Article

Agri-food by-products to fortify a fish-based food: a new approach to balance pro and cons of recycling

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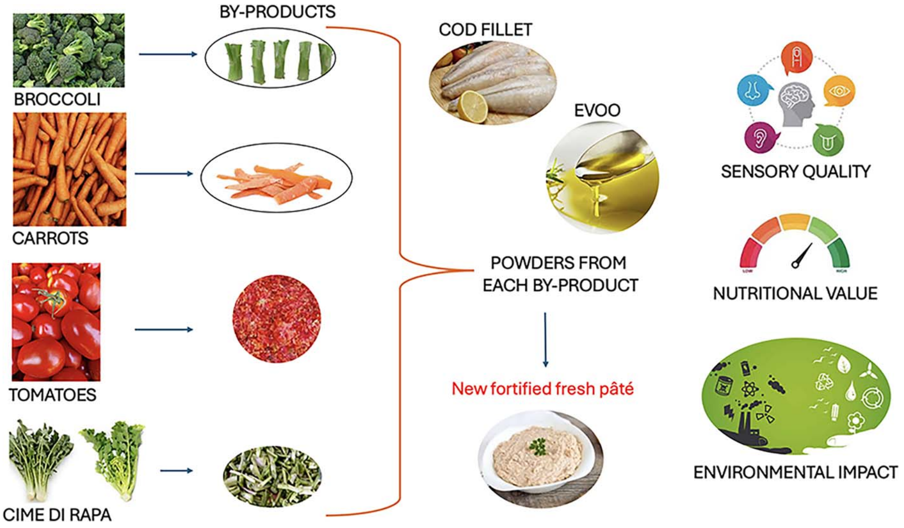
Abstract

Cod-based pâtés were developed using extra-virgin olive oil and by-products from broccoli, carrots, tomatoes (TPS), and *cime di rapa* (CdR), following dehydration and grinding treatments. The by-products were added up to the maximum level to maintain the pâté full sensory acceptance (score > 5 on a 9-point scale). Control and fortified formulations were assessed for antioxidant activity, total dietary fibre content, and the energy consumption associated with by-product processing. A life cycle assessment (LCA) was conducted to quantify the carbon footprint of each pâté. The optimal formulation required markedly different incorporation levels of by-products: TPS produced the least sensory impact (mass fraction 0.293), whereas CdR showed the most pronounced effect (mass fraction 0.129). The LCA consistently demonstrated a net reduction in terms of global warming potential, ranged from 1.13 to 0.12 kgCO_2eq, primarily driven by the displacement of high-impact ingredient (cod and extra virgin olive oil). The global quality index, utilized to balance antioxidant activity, fibre content, environmental impact, and sensory quality, identified TPS as the optimal by-product to be recycled.

Keywords: pâtéfood fortification, sustainability, recycling, by-products

Graphical abstract



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Introduction

The pâté is a food with a long gastronomic tradition, known and appreciated for its distinctive sensory characteristics. The traditional recipes are based on goose or pork liver (dos Santos Cruxen et al., 2021), though contemporary production utilizes a variety of other ingredients. Over time, the production of pâté has evolved to include other types of meat such as turkey, chicken, deer, and fish (Lazic et al., 2015; Nielsen et al., 2020; Vargas-Ramella et al., 2020). The fish industry has taken meat-based pâté production as a model for developing similar products made with various fish species, such as salmon, tuna, or anchovies. These products diversify the pâté market, offering distinct sensory characteristic and nutritional benefits associated with fish as the primary ingredient (Aquerreta et al., 2002). The beneficial properties of fishery products are well-documented in numerous scientific studies. Fishery products are recognized for their high biological value proteins, omega-3 polyunsaturated fatty acids, vitamins, and minerals, contributing to heart health, cognitive function, and overall well-being (Chen et al., 2022; Kharl et al., 2025). However, they are significantly deficient in compounds such as polyphenols, carotenoids, and dietary fibres that are the main bioactive compounds of fruit and vegetables, also available in agri-food by-products. For this reason, a proper combination of fish-based food and vegetable by-products could represent a promising strategy for fish product fortification and improved sustainability.

To date, to the best of our knowledge, there are no published examples of pâté fortified with agri-food by-products for human consumption. Efforts in this context have primarily focused on aquaculture feeds, where agricultural by-products are valorized to promote optimal fish growth and health (Kuebutornye et al., 2025), considering the well-known antioxidant, anti-inflammatory, and antimicrobial properties of agri-food by-products (Bianchi et al., 2021).

Most studies on fish-based pâté are dealing with shelf-life extension rather than on strategies to enhance the nutritional value. For example, the use of natural rosemary extracts, rich in terpenes, was useful to preserve the product from oxidative spoilage (Cedeño-Pinos et al., 2022). Similarly, the use of tilapia fillet residues enriched with oregano essential oil were shown to extend the product shelf life and reduce cadaverine levels (Matiucci et al., 2023).

Given this knowledge gap, the current study, for the first time, investigated new pâtés fortified with by-products from tomatoes, carrots, *cime di rapa* (CdR), and broccoli (BR). The selection of these by-products is justified by their known beneficial properties. Tomato seeds and peels are widely recognized as source of high-value compounds with potential applications in various sectors, including food, pharmaceutical, medical, and packaging (Rouhou et al., 2024). Similarly, carrot by-products are valuable source of bioactive compounds, including dietary fibre, carotenoids, β-carotene, vitamins (such as thiamine, riboflavin, folic acid, and the B-complex group), and essential minerals like calcium, copper, magnesium, potassium, phosphorus, and iron (Luca et al., 2022). A recent study on Brassicaceae valorization pathways, specifically examining BR leaves and stems, demonstrated the presence of glucosinolates, which are precursors of isothiocyanates, substances known for their anticancer and antimutagenic properties, such as sulforaphane and sulforaphane (Artés-Hernández et al., 2023). *Cime di rapa* by-products are also rich in polyphenols and have found applications in food preservation, as natural alternative to synthetic additives (Baiano et al., 2024).

Food fortification with vegetable by-products represents a valid opportunity for the industry, particularly as the recovery and valorization of food waste have emerged as key strategies to mitigate the industry's significant contribution to greenhouse gas emissions and climate change (Rahman et al., 2024). According to the European (EU) Directive 2018/851, a *by-product* is defined as a substance or object resulting from a production process that was not primarily intended to produce that substance or object (Directive EU, 2018/851). The integration of by-products into industrial processes can both increase product value and reduce production costs (Orozco-Angelino et al., 2023). Furthermore, within a circular economy framework, this strategy contributes to greenhouse gas reduction and promotes the sustainable growth of the bioeconomy across industrial sectors (Gómez-García et al., 2021).

Based on these considerations, this study aimed to develop acceptable pâtés fortified with by-products and determine their enhanced nutritional quality in terms of antioxidant activity and fibre content, compared to a traditional control product. A secondary objective was to assess the environmental performance, specifically the carbon footprint, resulting from the partial substitution of cod content with plant-based by-product. This analysis aimed to assess the effectiveness of various by-products used as substitutes for cod, whose contribution to the overall carbon footprint is particularly high compared to other food categories (Bruno et al., 2019). Finally, a global quality index (*GQI*) was calculated by balancing the benefits (i.e., antioxidant activity, fibre content and environmental impact) against the drawbacks (sensory quality) of pâté fortification to identify the optimal by-product for valorization.

Materials and methods

Raw materials

By products from BR (*Brassica oleracea*) were obtained from Farris Srl (Giardinetto, Foggia, Italy), and tomato peels and seeds (cv. Taylor) were supplied by RossoGargano (Foggia, Italy). By-products from CdR (*Brassica rapa sylvestris*) and carrots (*Daucus carota*) were generated from raw materials purchased at a local market (Foggia, Italy). The carrot peels, CdR by-products, and BR by-products were initially washed in water, then sanitized by immersion in chlorinated water (20 ml/L) for 5 min, and subsequently rinsed with pure water and air dried. To prevent degradation, all by-products were immediately stored at −18 °C, until use.

Prior to dehydration, each type of by-products was defrosted under refrigeration. Dehydration was subsequently carried out using a conventional dryer (PF–SICCO80PRO, SICCOTECH, Campobasso, Italy). The dryer has a cabinet volume of 0.6 m^3, operating at atmospheric pressure with a relative humidity of 5% and a temperature of 60 °C. Approximately 6 kg of each by-product was distributed across 15 racks (72 × 53 × 3 cm) to ensure a thin and uniform layer. According to the methodology reported by Lordi et al. (2025a), drying data were periodically recorded by weighing 5 g samples using a thermal balance (Sartorius, Gottingen, Germany) set at 130 °C. The process was terminated when the sample weight remained constant across consecutive measurements. The dried by-products were ground using a laboratory grinder to obtain a fine powder ($< 500\ \mu m$) and stored in plastic bags at 4 °C in an environment protected from light.

Pâté production

Refrigerated cod fillets and extra virgin olive oil were adopted as basic ingredients for the pâté samples. Cod was selected due

Table 1. Formulation of cod pâtés in terms of weight fraction of each ingredient.

Ingredients	CTRL	TPS	CP	BR	CdR
Cod fish	0.692	0.165	0.344	0.184	0.236
Extra virgin oil	0.308	0.073	0.153	0.082	0.105
By-product powder	0.000	0.293	0.229	0.163	0.147
Water to hydrate by-product powder	0.000	0.469	0.275	0.571	0.513

Note. BR = broccoli; CdR = *cime di rapa*; CP = carrot peels; CTRL = control; TPS = tomato peels and seeds.

to its commercial availability, moderate cost, and common consumption. Both ingredients were procured form a local market (Foggia, Italy). The cod fillets were defrosted under refrigeration, cut, and subsequently boiled in water at 100 °C for 5 min. A total of five cod-based pâtés were prepared: a control sample (CTRL) consisting of 45 g of cod and 20 g of extra virgin olive oil blended without any by-products, and four samples containing the respective by-product powders, prehydrated with water. The fortified pâté samples were designated as: TPS (tomato peels and seeds), CP (carrot peels), BR, and CdR.

Recipe optimization aimed to maximize the by-product content while maintaining overall product quality within an acceptable sensory range. Specifically, the by-product concentration was increased until the overall quality score decreased from the maximum (9) to an acceptability value between 6 and 7. The amount of water used for by-product prehydration was determined to facilitate the highest possible incorporation of the by-product into the final recipe. Prehydration was found to improve key sensory attributes, specifically spreadability and taste. The optimized recipes, with each formulation in terms of weight fraction of its components, are presented in Table 1.

Chemical analyses

All reagents, including Folin–Ciocalteu reagent, gallic acid monohydrate, 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), aluminium chloride, sodium nitrite, sodium acetate buffer solution (3M), sodium hydroxide solution, 2,4,6-tripyridyl-s-triazine, iron sulphate heptahydrate, and quercetin, were supplied by Sigma-Aldrich (Milan, Italy). Anhydrous sodium carbonate was obtained from Carlo Erba (Milan, Italy). All chemicals were of analytical grade. To determine the antioxidant activity, sample extraction was first performed. The pâté samples were dried using a ventilated oven (BINDER GmbH, Tuttlingen, Germany) at 35 °C and subsequently milled to a fine powder. Each by-product, being already available as powder, was analysed without previous extraction. The methanolic extract was obtained by mixing 2 g of dried powder with 20 ml of methanol acidified with 1% HCl (vol/vol). The mixtures were shaken, centrifuged, and the resulting supernatant was collected and filtered for analysis. The antioxidant activity was assessed using the ABTS assay, as described by Panza et al. (2022) and the Ferric Reducing Antioxidant Power (FRAP) assay, as described by Marinelli et al. (2021). The ABTS results were expressed as milligrams of Trolox equivalents (TE)/g of dry weight (dw), based on a calibration curve ranging from 12.5 and 500 mg/L ($R^2 = 0.990$). The FRAP results were expressed as μmol of ferrous equivalent Fe (II)/g of dw, using a calibration curve established between 0.1 and 0.8 mmol/L ($R^2 = 0.993$). All analyses were performed in triplicate.

Sensory analysis

The sensory evaluation of the cod pâté samples was performed using the quantitative descriptive analysis method. The trained sensory panel consisted of seven qualified panellists (age between 30 and 50 years), researchers of Food Department, all possessing several years of prior experience in food product evaluation. Panellists underwent 2 days (one session/day; 2 h/session) to establish specific sensory attributes, minimize inter-individual variability, and ensure result repeatability. Panellists were asked to evaluate samples based on the following attributes: odour, colour, appearance, fish flavour, spreadability, and taste. Spreadability was evaluated by assessing how smoothly and uniformly the fish pâté could be applied, offering insight into its overall tactile quality. Additionally, a measure of global acceptance (overall quality) was collected. A structured 9-point scale was utilized for the scoring of each attribute, ranging from 1 to 9. The scale limits were specifically defined, with a score of 5 representing the acceptable limit and scores ≥6 indicating acceptance (e.g., 6 = Reasonable, 7 = Good, 8 = Very Good, 9 = Excellent). Given that the samples were prepared following the good manufacturing practices and contained no ingredients posing a known risk, the study was classified as exempt from formal Institutional Ethics Committee review. Nonetheless, 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.

Total dietary fibre content

The total dietary fibre (TDF) content of all by-products and pâté formulations was measured by NIRO SRL laboratory (Campobasso, Italy) according to the AOAC Official Method (2003). Results were expressed in g/100 g of the sample.

By-product water content

The water content by-product was evaluated according to the following equation:

$$C(t) = \frac{W(t) - W_F}{W_F} \bullet 100 \tag{1}$$

where $C(t)$ is the sample water content at time t expressed as $\left[\frac{g\ water}{100\ g\ dry\ matter}\right]$, W(t) is the weight of sample at time t expressed as $[g]$, W_F is the weight of the sample after it has been kept at 130 °C until all the water was desorbed, it was expressed as $[g]$.

The amount of desorbed water at time t $\left(M_{H_2O}(t)\right)$ was calculated according to the following equation:

$$M_{H_2O}(t) = C_0 - C(t) \tag{2}$$

where C_0 is the initial water content of the sample. The amount of desorbed water at equilibrium $\left(M_{H_2O}^{\infty}\right)$ was estimated according to the following expression:

$$M_{H_2O}^{\infty} = C_0 - C_{\infty} \tag{3}$$

where C_∞ is the sample water content at the termination of the dehydration process.

Energy consumption of the by-product's dehydration process

The procedure used by Le Rose et al. (2025) to determine the amount of energy consumed per gram of dehydrating by-product ($\widetilde{E}(t)$) was used in this work. In summary, the by-product dehydration kinetic was described using the following relationships:

$$0 \le t \le t_c$$

$$M_{H_2O}(t) = K_1 \bullet t \tag{4}$$

$$t > t_c$$

$$M_{H_2O}(t) = K_1 \bullet t_c + K_2 \bullet \left\{ 1 - \exp\left[-(t - t_c) \bullet \left(\frac{K_1}{K_2} \right) \right] \right\} \tag{5}$$

where K_1 is the desorption rate during the first stage $\left[\frac{g\ desorbed\ water}{100\ g\ dry\ matter} \bullet \frac{1}{\text{min}} \right]$, K_2 is the maximum amount of water desorbed during the second stage $\left[\frac{g\ desorbed\ water}{100\ g\ dry\ matter} \right]$, t_c is the moment in which the transition from one stage to another takes place, t is the dehydration time. The reader is invited to refer to the study of Conte et al. (2024) for a detailed description of the model used to describe the dehydration kinetic, and the hypotheses used to derive it.

The amount of energy consumed per gram of dehydrating by-product is related to the extent of the dehydration process through the following expressions:

$$0 \le \mathbf{ext\%} \le \frac{K_1 \bullet t_c}{M^{\infty}_{H_2O}} \bullet 100$$

$$\widetilde{E}\,(\mathbf{ext\%}) = \frac{\gamma \bullet \left(\frac{M^{\infty}_{H_2O}}{K_1 \bullet 100} \bullet \mathbf{ext\%} \right)}{m^0_{Tot} \bullet \left(1 - \frac{x^0_{dm}}{100} \bullet \mathbf{ext\%} \bullet \frac{M^{\infty}_{H_2O}}{100} \right)} \tag{6}$$

$$\mathbf{ext\%} > \frac{K_1 \bullet t_c}{M^{\infty}_{H_2O}} \bullet 100$$

$$\widetilde{E}\,(\mathbf{ext\%}) = \frac{\gamma \bullet \left[t_c - \ln\left(\frac{K_1 \bullet t_c + K_2 - \mathbf{ext\%} \bullet \frac{M^{\infty}_{H_2O}}{100}}{K_2} \right) \bullet \frac{K_2}{K_1} \right]}{m^0_{Tot} \bullet \left(1 - \frac{x^0_{dm}}{100} \bullet \mathbf{ext\%} \bullet \frac{M^{\infty}_{H_2O}}{100} \right)} \tag{7}$$

where γ is the energy power provided to the dehydrator, **ext%** is the extent of the dehydration process, m^0_{Tot} is the initial value of the mass of dehydrating by-product, x^0_{dm} is the initial value of dry matter mass fraction. The reader is invited to refer to the study of Le Rose et al. (2025) for a detailed description of the procedure used in this work to determine the amount of energy consumed per gram of dehydrated by-product.

Environmental impact assessment

The life cycle assessment (LCA) approach provides a comprehensive framework for evaluating the environmental burdens and benefits of a product or service across its entire life cycle—from raw material acquisition to final disposal (Klöpffer, 1997). In the present study, the LCA was conducted in accordance with the International Organization for Standardization (ISO) 14040 series standards (ISO, 2006a, 2006b), encompassing the four mandatory phases: goal and scope definition, inventory analysis, impact assessment, and interpretation of results. The agri-food by-products utilized in the pâté were considered generic biowaste and were assigned a "burden-free" status; thus, the environmental impacts associated with their initial production were excluded. The functional unit, which serves as the measurable reference for the product's function, was defined as 1 kg of pâté for all impact assessment (Arzoumanidis et al., 2020). Environmental impact data for the extra virgin olive oil were sourced from the environmental product declaration of Deoleo (Environdec, 2023), as specific data were not available in the consulted database. Due to the absence of "cod fish" in the utilized database, "fresh hake," related to the Spanish territory, was selected as a substitute. Although hake and cod belong to different families, both are part of the order *Gadiformes* and share several morphological and biological characteristics typical of white-fleshed demersal fish (Feketea et al., 2021). Furthermore, hake caught by trawling was selected, as this is the most common fishing method, also used for cod in Europe, although it is known to have a higher impact on marine ecosystems (Ortega et al., 2023).

During the life cycle inventory phase, primary data, specifically the energy demand associated with the laboratory-scale dehydration and grinding of by-products, were collected directly from the University of Foggia laboratory. For the Life Cycle Impact Assessment, the contributions of the life cycle inventory inputs and outputs were quantitatively assessed using the "CML-IA baseline v. 3.11" methodology, implemented in the SimaPro software (v. 10.2.0.3). The selected environmental indicator was global warming potential (GWP100), with results expressed in kilograms of CO_2 equivalent ($kgCO_2eq$).

Global quality index calculation

The procedure used by Lordi et al. (2025b) was used to calculate the *GQI*. The positive aspects associated with fortification are related to both the reduced impact on the environment and to the increased antioxidant activity (ABTS and FRAP) and fibre content (TDF); the negative aspect associated with fortification is sensory quality.

The normalization of the quality indices was made according to the following expressions:

$$\textit{Normalized Environmental Impact} = \frac{\left| PQI^{CTR}_{EI} - PQI^{Act}_{EI} \right|}{PQI^{CTR}_{EI}} \bullet 100 \tag{8}$$

$$\textit{Normalized Total Dietary Fiber} = \frac{\left| PQI^{CTR}_{TDF} - PQI^{Act}_{TDF} \right|}{PQI^{CTR}_{TDF}} \bullet 100 \tag{9}$$

$$\textit{Normalized FRAP} = \frac{\left| PQI^{CTR}_{FRAP} - PQI^{Act}_{FRAP} \right|}{PQI^{CTR}_{FRAP}} \bullet 100 \tag{10}$$

$$\textit{Normalized ABTS} = \frac{\left| PQI^{CTR}_{ABTS} - PQI^{Act}_{ABTS} \right|}{PQI^{CTR}_{ABTS}} \bullet 100 \tag{11}$$

$$\textit{Normalized Sensory Quality} = \frac{\left| NQI^{CTR}_{SQ} - NQI^{Act}_{SQ} \right|}{NQI^{CTR}_{SQ}} \bullet 100 \tag{12}$$

where PQI^{CTR}_{EI} is the Quality Index of the control sample related to the Environmental Impact, PQI^{Act}_{EI} is the Quality Index of the active sample related to the Environmental Impact, PQI^{CTR}_{TDF} is the Quality Index of the control sample related to the TDF, PQI^{Act}_{TDF} is the Quality Index of the active sample related to the TDF, PQI^{CTR}_{FRAP} is the Quality Index of the control sample related to FRAP, PQI^{Act}_{FRAP} is the Quality Index of the active sample related to FRAP, PQI^{CTR}_{ABTS} is the Quality Index of the control sample related to ABTS, PQI^{Act}_{ABTS} is the Quality Index of the active sample related to ABTS, NQI^{CTR}_{SQ} is the Quality Index of the control sample related to the Sensory Quality, NQI^{Act}_{SQ} is the Quality Index of the active sample related to the Sensory Quality. It is worth noting that each one of the normalized quality indices represents the percentage difference between the active sample (i.e., the sample fortified with the investigated by-product) and the control. The *GQI* was calculated according to the following expression, considering the environmental impact and the chemical aspects equally weighted:

$$GQI = \frac{\frac{1}{2} \bullet \left(\frac{PQI_{EI}^{CTR} - PQI_{EI}^{Act}}{PQI_{EI}^{CTR}} \right) + \frac{1}{2} \bullet \left(\frac{\frac{PQI_{TDF}^{Act} - PQI_{TDF}^{CTR}}{PQI_{TDF}^{CTR}} + \frac{PQI_{FRAP}^{Act} - PQI_{FRAP}^{CTR}}{PQI_{FRAP}^{CTR}} + \frac{PQI_{ABTS}^{Act} - PQI_{ABTS}^{CTR}}{PQI_{ABTS}^{CTR}}}{3} \right)}{\frac{NQI_{SQ}^{CTR} - NQI_{SQ}^{Act}}{NQI_{SQ}^{CTR}}} \tag{13}$$

Statistical analysis

Experimental data were analysed using one-way analysis of variance. Tukey's honest significant difference test was subsequently performed to identify significant difference among samples ($p < .05$). All statistical analyses were performed using JMP 18 for Windows (JMP Statistical Discovery LLC 920 SAS Campus Drive Cary, NC 27513).

Results and discussion

Fortification with vegetable by-products presents several nutritional and environmental advantages; however, a primary concern is the potential compromise of the food's sensory quality. This section of results first analyzes the trade-offs between the advantages and disadvantages of the pâté fortification, discussing sensory quality, antioxidant activity, fibre content, and environmental impact deriving from recycling. These factors are then balanced to identify the most suitable and sustainable by-products for integration.

Sensory quality

Recipes were optimized such that the overall quality score for each pâté fell within the acceptable range of 6 and 7 (above the minimum acceptable threshold of 5). Consequently, the mass fraction of the by-product in the optimal formulations serves as an inverse measure of its sensory impact on the final product. A higher achievable weight fraction indicates a lower negative impact of the by-product on the pâté's sensory properties. As shown in Table 1, the maximum mass fraction of the incorporated by-products decreased in the order: TPS > CP > BR > CdR. This trend demonstrates that, among the tested ingredients, TPS exerted the least sensory impact, allowing for the highest incorporation rate, whereas CdR exhibited the most pronounced sensory impact. Direct comparisons with published literature are precluded due to the novelty of using these specific by-products in pâté formulation. Nevertheless, it is relevant to note that, unlike the other tested materials, TPS (tomato by-product) has been widely applied across various food categories, including pasta, bread, focaccia, sausages, and dairy products (Szabo et al., 2025). The observed low sensory impact of TPS can likely be attributed to the technological properties of its high fibre content, which enhances water holding and swelling capacity, and binds flavour component (Ratu et al., 2023). This mechanism generally contributes to improved sensory acceptance in food products.

Antioxidant activity and fibre content of pâtés

Table 2 summarizes the antioxidant activity, TDF content, and mass fraction of by-product for all optimized pâté formulations. As anticipated, the antioxidant activity of all fortified samples was significantly higher than that of the CTRL formulation. Among the fortified samples, the CdR pâté exhibited the highest antioxidant activity ($p < .05$). Conversely, the remaining fortified samples show similar values, without any statistically significant differences ($p > .05$). The results recorded on the fortified samples are justified by the antioxidant activity recorded on the raw materials. In fact, CdR had the highest antioxidant activity measured by both ABTS and FRAP methods: 6.56 ± 0.01 mg TE/g dw and 79.24 ± 0.67 μmol Fe (II)/g dw, respectively. The other ABTS values were 4.69 ± 0.06 mg TE/g dw for BR, 4.93 ± 0.05 mg TE/g dw for CP and 3.13 ± 0.41 mg TE/g dw for TPS, whereas the other FRAP values were 52.20 ± 0.84 μmol Fe (II)/g dw for BR, 56.60 ± 0.84 μmol Fe (II)/g dw for CP, and 10.79 ± 0.42 μmol Fe (II)/g dw for TPS. Regarding TDF content, all fortified pâtés presented values substantially higher than the control sample. The TPS formulation demonstrated the highest TDF content increase, whereas BR and CdR resulted in the smallest enhancements. The TDF of the original by-products justifies the results recorded on pâté, being the TDF for tomato by-products equal to 66.2 ± 3.80 g/100 g, for CdR equal to 28.4 ± 1.63 g/100 g, for BR equal to 38.9 ± 2.24 g/100 g, and for CP equal to 24.1 ± 0.27 g/100 g.

As anticipated, the pâté fortification with the tested by-products significantly enhanced both antioxidant activity and fibre content. The observed variability among the fortified samples is attributable to a combination of the specific mass fraction incorporated and the intrinsic phytochemical and fibrous capacity of each by-product. Regarding the antioxidant activity, a notable inverse correlation was observed: the activity increased as the by-product mass fraction decreased (Table 2). This demonstrates that the observed gains are primarily driven by the intrinsic antioxidant potency of the incorporated materials, rather than their quantity. In essence, CdR exhibits the highest intrinsic antioxidant activity among the studied by-product, while TPS, CP, and BR possess largely comparable potency. This finding is well supported by the literature, where studies on turpin tops consistently highlight an abundance of flavonoids, particularly glycosylated derivatives of kaempferol, quercetin, and isorhamnetin as main phenolic compounds responsible for their significant antioxidant activity (Chihoub et al., 2019; Romani et al., 2006). Conversely, the fibre content of the fortified pâté demonstrated a clear increase with the by-product mass fraction. Furthermore, the nonlinear relationship between the mass fraction and fibre content suggests that, alongside mass inclusion, the intrinsic fibre composition of the by-product significantly influences the final TDF value. Consequently, the TPS is identified as the by-product that most effectively contributes to increasing the fibre content, while BR and CdR are the least effective. This aligns with chemical characterization studies on tomato pomace, which confirm that its substantial compound is primarily insoluble dietary fibre (Gu et al., 2020). Furthermore, the industrial relevance of this finding is underscored by recent work in Tunisia, a major tomato producing country, where optimized laboratory conditions are being explored for pilot-scale fibre extraction from tomato pomace (Rouhou et al., 2024). Our findings regarding the significant fibres content of carrot pomace are corroborated by external evidence; for instance, Luca et al. (2022) characterized four varieties of carrot pomace powders, reporting high fibres contents ranging from 20.09% to 33.34%, that are in line with our results.

Energy consumption of by-product dehydration process

Figure 1 illustrates the dehydration kinetics of the investigated by-products. The curves presented the best fit of the kinetic model

Table 2. Antioxidant activity (ABTS and FRAP) and total dietary fibre (TDF) of pâté samples.

Samples	By-product mass fraction	ABTS [mg TE/g dw]	FRAP [µmol Fe (II)/g dw]	TDF [g/100 g]
CTRL	0.000	0.985 ± 0.04^c	3.67 ± 0.07^c	0.60 ± 0.045^d
TPS	0.293	2.359 ± 0.71^b	9.31 ± 0.32^b	16.40 ± 0.951^a
CP	0.229	2.977 ± 0.58^b	12.16 ± 3.59^b	8.90 ± 0.521^b
BR	0.163	2.765 ± 0.25^b	9.12 ± 0.39^b	5.10 ± 0.303^c
CdR	0.147	6.349 ± 0.17^a	27.82 ± 4.05^a	5.00 ± 0.297^c

Data are presented as mean ± SD. Data in each column with different superscript letters are statistically different ($p < .05$). *Note.* ABTS = 2,2-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt; BR = broccoli; CdR = *cime di rapa*; CP = carrot peels; CTRL = control; TPS = tomato peels and seeds.

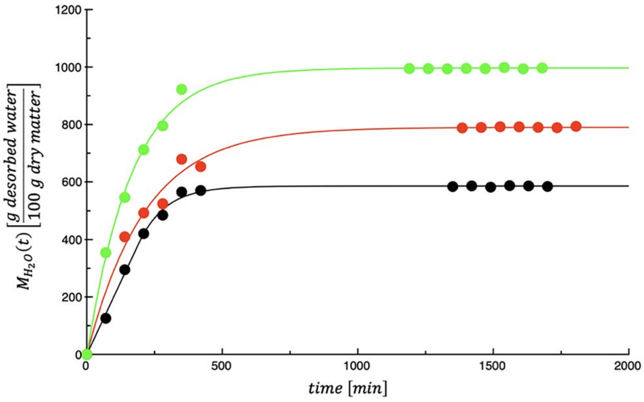

Figure 1. Dehydration kinetic of by-products. ● CP, ● CdR, ● BR. BR = broccoli; CdR = *cime di rapa*; CP = carrot peels.

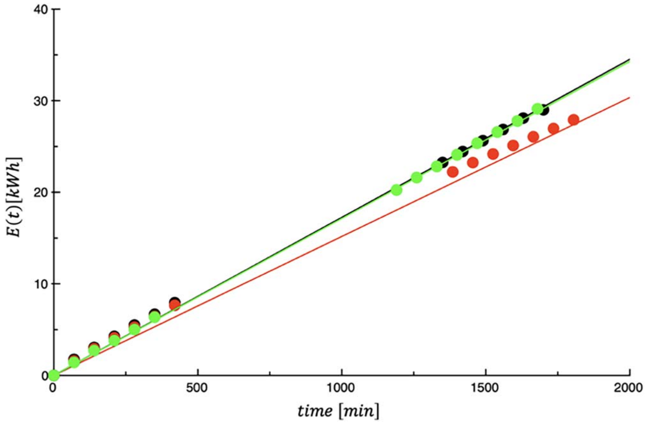

Figure 2. Amount of energy supplied to the dehydrator [$E(t)$] plotted as a function of time. ● CP, ● CdR, ● BR. BR = broccoli; CdR = *cime di rapa*; CP = carrot peels.

proposed by Conte et al. (2024) (i.e., equations (4) and (5)) to the experimental dehydration data. Note that TPS data were not included in Figure 2 because the TPS data were sourced from the same batch previously characterized by Lordi et al. (2025a). For further details regarding the TPS dehydration kinetics and the calculation of energy consumption, the reader is referred to Lordi et al. (2025a) manuscript.

The mean relative deviation modulus $\left(\bar{E}\%\right)$ was used to measure the goodness of fit (Buonocore et al., 2003):

$$\bar{E}\% = \frac{100}{N} \bullet \sum_{i=1}^{i=N} \frac{\left|M_i^{exp} - M_i^{pred}\right|}{M_i^{exp}} \tag{14}$$

N is the number of experimental data, M_i^{exp} is the experimental value, M_i^{pred} is the predicted value.

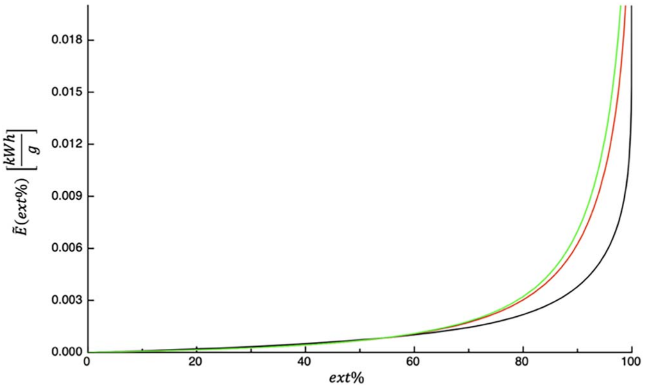

Figure 3. Energy consumption per gram of dehydrated food ($\tilde{E}$ (**ext**%)) plotted as a function of **ext**%. ——— CP, ——— CdR, ——— BR. BR = broccoli; CdR = *cime di rapa*; CP = carrot peels.

The values of model's parameter, obtained by fitting the dehydration kinetics, along with the calculated values of $\bar{E}\%$ are listed in Table 3. As can be inferred from the $\bar{E}\%$ values shown in the table, the model proposed by Conte et al. (2024) adequately describes the dehydration kinetic of the by-products tested in this study.

Figure 2 illustrates the energy consumed by the dehydrator ($E(t)$) plotted as function of time. The curves shown in this figure represent the best linear fit passing through the origin of data. The calculated values for the slope of the straight line (i.e., γ) are shown in Table 3 along with the calculated value of $\bar{E}\%$.

As can be seen in Table 3, the values of $\bar{E}\%$ for the consumption energy of CP and CdR by-products are not as good as that obtained for BR and those previously obtained for the dehydration kinetics; however, they can be considered acceptable. Considering the calculated γ values, the differences among the samples are small and can be considered negligible.

Figure 3 shows $\tilde{E}$ (**ext**%) plotted as a function of **ext**%. The curve shown in the figure were predicted by means of equations (6) and (7). The values of the parameters appearing in the above-mentioned equations are those listed in Table 3. The amount of energy consumed per gram of dehydrating by-product was calculated by setting the extent of the dehydration process at 99% (i.e., $\tilde{E}$ (99%)), the obtained values for CP, CdR, and BR are listed in Table 3, whereas $\tilde{E}$ (99%) of TPS is 0.003388 $\left[\frac{kWh}{g}\right]$ (Lordi et al., 2025a). As can be inferred from the calculated values of $\tilde{E}$ (99%), there are marked differences among the investigated by-products. This is most probably due to the fact that the initial water content greatly changes from one by-product to another.

Figure 4 shows $\tilde{E}$ (99%) plotted as a function of the initial by-product water content (i.e., $1 - x_{dm}^0$), the curve shown in the figure

Table 3. Parameters used to estimate $\tilde{E}$ (99%) and $\bar{E}$% for dehydration kinetics and energy consumption.

Parameters	CP	CdR	BR
t_c [min]	$1.91 \cdot 10^{2}$	$1.46 \cdot 10^{-5}$	$1.75 \cdot 10^{1}$
$k_1 \left[\frac{g\ desorbed\ water}{100\ g\ dry\ matter} \bullet \frac{1}{\mathrm{min}}\right]$	2.02	3.68	5.46
$k_2 \left[\frac{g\ desorbed\ water}{100\ g\ dry\ matter}\right]$	199.80	789.74	901.08
$\gamma \left[\frac{kWh}{\mathrm{min}}\right]$	$1.73 \cdot 10^{-2}$	$1.52 \cdot 10^{-2}$	$1.71 \cdot 10^{-2}$
x_{dm}^{0}	$1.45 \cdot 10^{-1}$	$1.13 \cdot 10^{-1}$	$9.18 \cdot 10^{-2}$
m_{Tot}^{0} [g]	6,000	6,000	5,297.40
$\bar{E}$% dehydration kinetic	2.19	2.10	1.02
$\bar{E}$% energy consumption	8.30	11.37	2.88
$\tilde{E}$ (99%) $\left[\frac{kWh}{g}\right]$	0.009672	0.02082	0.02616

Note. BR = broccoli; CdR = *cime di rapa*; CP = carrot peels.

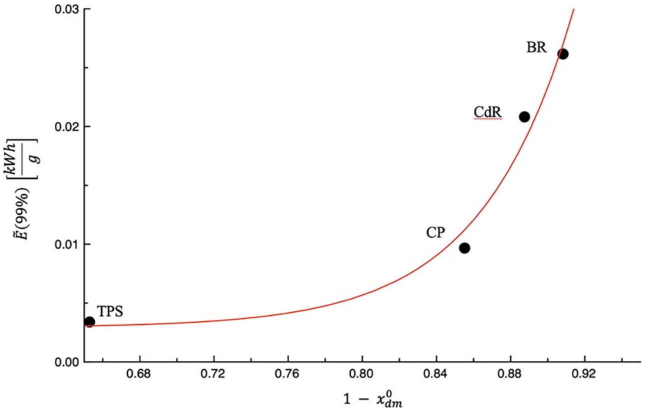

Figure 4. Energy consumption per gram of dehydrated food ($\tilde{E}$ (99%)) plotted as a function of the initial water mass fraction ($1 - x_{dm}^{0}$).

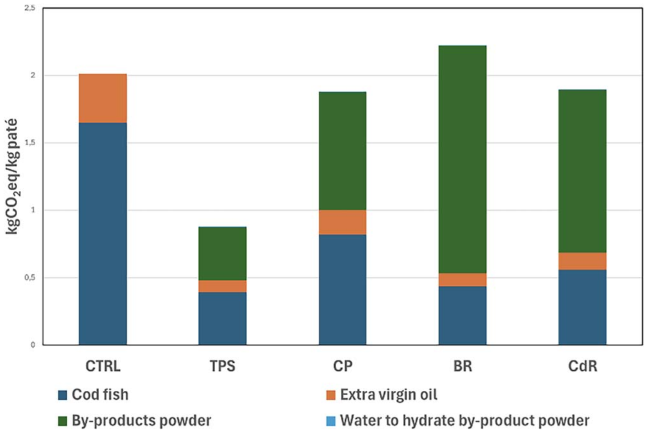

Figure 5. Carbon footprint of pâtés, expressed in $kgCO_2eq$ per kg of product. Contributions of individual ingredients are colour-coded.

was drawn only to emphasize the trend of data. As can be seen from the figure, the increase of $\tilde{E}$ (99%) with $(1 - x_{dm}^{0})$ is more than linear. This is due to two main reasons, the first is that as the initial water content increases, the time needed to bring the by-product to a 99% dehydration level increases; the second is that starting from the same amount of by-product, as the initial water content increases, the amount of product dehydrated to 99% decreases. Both the above factors contribute to making the dependence of $\tilde{E}$ (99%) on $1 - x_{dm}^{0}$ more than linear. Considering the limited number of data available, and the fact that only one dehydration technique was used in this investigation, it is not possible to state whether or not the trend shown in the figure can be extended to other by-products.

Environmental impact of pâté samples

This section presents the LCA, focusing on the environmental impact, expressed as the carbon footprint, of the control pâté and the fortified formulations. In terms of GWP, the production of 1 kg of pâté enriched with TPS, CP, BR, and CdR leads to reductions of 1.13 $kgCO_2eq$, 0.13 $kgCO_2eq$, no reduction (more specifically, 0.20 $kgCO_2eq$ higher than the control), and 0.12 $kgCO_2eq$, respectively, compared to 1 kg of traditional pâté. A comparative analysis of the scenarios indicates that the largest contribution to the carbon footprint reduction arises from the decreased use of cod, followed by a reduction in extra virgin olive oil, both used in varying proportions according to the specific mass fraction of by-products incorporated in each formulation (Table 1). This pattern is shown in Figure 5. Furthermore, as illustrated in Figure 5, the contribution to the GWP also includes emissions associated with the electricity consumption required for the laboratory-scale dehydration and grinding of the by-products. The energy consumption diagram (Figure 4) indicates a progressive increase in energy demand for these processes in the order of TPS < CP < CdR < BR. This sequence directly correlates with the emissions reported in Figure 5, thus demonstrating the direct relationship between the energy intensity of the by-product and the resulting carbon footprint. This relationship highlights the critical importance of optimizing energy efficiency in by-product processing to maximize the overall environmental benefits. Based on the results presented, the implementation of incorporating plant-based by-products into cod-based pâté at industrial scale could yield substantial benefits, particularly through a marked reduction in CO_2 equivalent emissions. Specifically, the replacement of animal-derived ingredients results in considerable environmental benefits in terms of greenhouse gas emissions, given the well-documented high carbon footprint of these products (Nijdam et al., 2012). Moreover, this approach facilitates substantial resource savings, a matter of critical importance considering the ongoing global decline in fish stocks (Barbeaux et al., 2020; Myers et al., 1997). The reduction in the use of marine resources, promoting their conservation and sustainable exploitation achievable through the adoption of similar strategies, directly aligns with one of the Sustainable Development Goals (SDGs) established by the

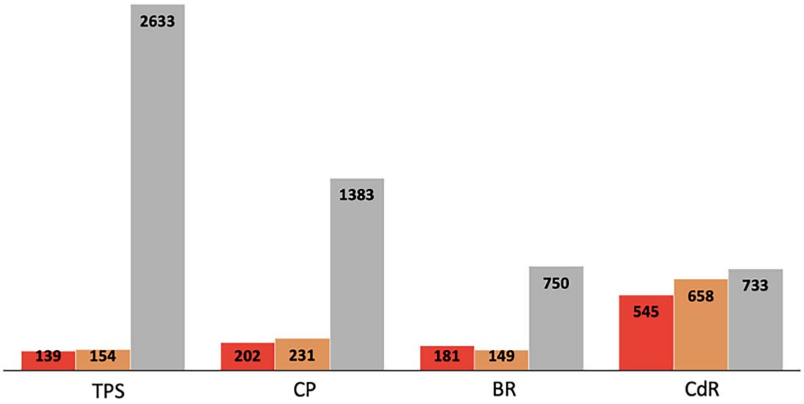

Figure 6. Normalized quality index associated with nutritional quality of the fortified pâté. Normalized ABTS index (first), normalized FRAP index (second), normalized fibre index (third). ABTS = 2,2-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt.

United Nations as part of the 2030 Agenda, specifically SDG-14 (European Commission, 2019).

Global quality index

The *GQI* as defined in the study of Lordi et al. (2025b) was employed to select the optimal fortified sample by systematically assessing the positive and negative aspects of the by-products. In fact, the numerator of equation (13) is the arithmetic average of the normalized environmental impact, antioxidant activity, and fibre content of the fortified pâtés. Conversely, the denominator represents the normalized quality index associated with the sole negative aspect, the pâté sensory quality. A *GQI* value greater than 1 indicates that the positive aspects of fortification outweigh the negative aspects. Conversely, a *GQI* value lower than 1 suggests that the drawbacks predominate. Furthermore, the sample exhibiting the highest *GQI* is considered the best performing formulation, as it the most effective balance between the studied positive and negative factors.

Figure 6 displays the normalized indices associated with antioxidant activity and fibre content of the fortified pâtés. As the data illustrate, all the normalized values are significantly greater than 1, confirming that the enrichment process effectively and significantly improved the pâté's profile. This outcome aligns with numerous studies demonstrating successful food fortification using specific by-products: brassica (Artés-Hernández et al., 2023), tomato (Szabo et al., 2025), carrot (Sharma et al., 2024), and turpin tops (Chihoub et al., 2019).

Figure 7 presents the normalized index associated with the environmental impact, alongside the average normalized index for the pâté quality relative to antioxidant activity and fibre content. As evident from the figure, while a quantifiable environmental benefit is associated with the use of three of tested by-products (TPS, CP, and CdR), the magnitude of these benefits is significantly lower than that derived from the enhancement of the pâté quality relative to antioxidant activity and fibre content. This pronounced disparity is primarily a consequence of the low baseline levels of fibre and antioxidant activity characterizing the control sample, which maximizes the perceived nutritional improvement.

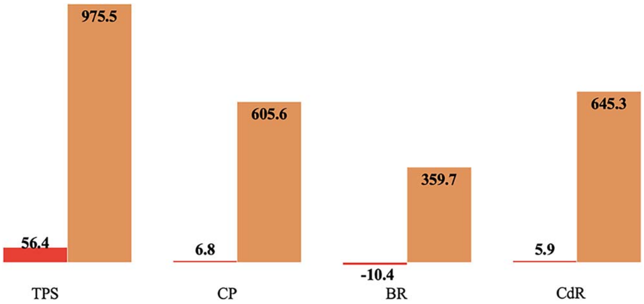

Figure 7. Normalized index associated with the environmental impact and the average of the normalized index associated with the pâté nutritional quality. Normalized environmental impact index (first); average of the normalized nutritional quality index (second).

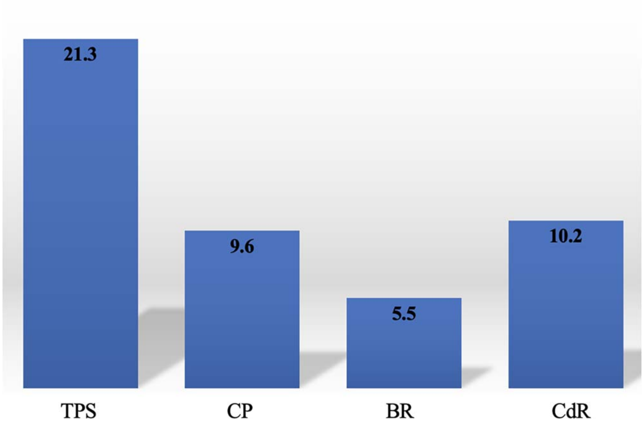

Figure 8. Values of *GQI* calculated by using equation (13) for the different fortified pâtés. *GQI* = global quality index.

By comparing the numerator and denominator of equation (13), i.e., the overall advantages of fortification significantly outweigh the associated sensory disadvantage. The average normalized benefits (numerator) were particularly high for the TPS formulation (515.9), followed by CdR (325.6), CP (306.2), and BR (174.7). Conversely, the normalized sensory drawback (denominator) was lowest for TPS pâté (24.2), while all other fortified products (CP, CdR, BR) shared a similar, slightly higher drawback value of 31.8. These data were used to calculate the *GQI*, which, critically, was found to be consistently greater than 1 for all sample types (Figure 8). Among the samples considered, the pâté with TPS exhibited the highest *GQI* value (i.e., the best balance between positive and negative factors). The BR pâté resulted the lowest *GQI* score. The CP and CdR fortified pâtés showed comparable *GQI* values, placing them in an intermediate category. The superior performance of the TPS formulation is mainly driven by the substantial increase in fibre content compared to the control, combined with environmental benefits among the sample studied, coupled with the least negative impact on sensory properties.

Conclusion

New cod-based pâtés were successfully developed *via* fortification with agri-food by-products sourced from broccoli, carrots, tomatoes, and CdR. The results demonstrated that selected by-products differentially affected the sensory acceptance of pâté, requiring varying incorporation rates to maintain an acceptable quality threshold. The maximum achievable mass fraction increased in the order: CdR (0.147) < BR < CP < TPS (0.293). Chemical analyses revealed that all fortified samples surpassed the control pâté quality, but trade-offs were evident: the sample containing CdR exhibited the highest antioxidant activity, driven by its intrinsic phytochemical potency. The pâté fortified with tomato peel and seeds (TPS) was superior in terms of fibre content. The LCA highlighted that the recycling of all tested agri-food by-products is an effective strategy to mitigate the carbon footprint associated with conventional pâté production, primarily due to the displacement of high-impact, animal-derived ingredients (cod). If the approach is adopted at large scale, the observed environmental savings per kilogram of pâté are directly scalable to larger production volumes, making these results highly relevant for the industrial sector and the sustainable goals of the 2030 Agenda. The final *GQI* analysis confirmed that the TPS formulation achieved the best overall balance, providing higher benefits with the least negative impact on sensory quality. Future research should evaluate the economic viability of this process using different fish species and various combinations of agri-food by-products. Such studies should also quantify the full nutritional profile of the fortified food, specifically analysing variations in protein and fat content following by-product addition.

Supplementary material

Supplementary material is available at *International Journal of Food Science and Technology* online.

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

Maria Luigia di Corcia (Formal analysis [equal], Writing—original draft [equal]), Alessia Le Rose (Formal analysis [equal], Writing—original draft [equal]), Chiara Russo (Formal analysis [equal], Writing—original draft [equal]), Dario Caro (Conceptualization [equal], Data curation [equal], Writing—original draft [equal]), Matteo Alessandro Del Nobile (Conceptualization [equal], Data curation [equal], Writing—review & editing [equal]), and Amalia Conte (Conceptualization [equal], Visualization [equal], Writing—review & editing [equal]). All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

None declared.

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