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Vegan burgers fortified with agri-food by-products: nutritional enhancement, energy consumption and LCA

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The agri-food industry faces significant challenges in waste management, with by-products from fruit and vegetable processing contributing to a considerable environmental footprint. This study addresses these issues by exploring the innovative upcycling of fruit and vegetable by-products as a sustainable source of dietary fiber to fortify vegan burgers. We developed novel formulations by incorporating by-products from prickly pears, artichokes, carrots and broccoli and systematically evaluated their impact on product quality. Our research focused on three critical aspects: sensory analysis, nutritional evaluation, and environmental impact. The results reveal that incorporating these sustainable ingredients significantly enhanced the nutritional profile; specifically, the prickly pear peel fortification led to the highest antioxidant activity (5.40 ± 0.19 mg Trolox per g for ABTS and 24.14 ± 1.43 μmol Fe(II) per g for FRAP). From an environmental point of view the significant energy requirement to dehydrate and grind by-products contributes to the overall environmental burden of the new vegan burger formulations. In particular, the CTRL formulation exhibited the lowest carbon footprint (0.90 kgCO_2eq per FU), compared with formulations containing artichoke by-products (1.02 kgCO_2eq per FU), turnip tops by-products (1.10 kgCO_2eq per FU), carrot peel by-products (1.25 kgCO_2eq per FU), prickly pear peel by-products (1.31 kgCO_2eq per FU), and broccoli by-products (1.85 kgCO_2eq per FU). These results highlight the importance of considering the energy demand to ensure environmentally sustainable recycling processes. Although this strategy is a promising direction for the future of food production, the economic viability requires further optimization.

Sustainability spotlight

The study successfully establishes a proof of concept for a circular economy model within the food industry, where waste is minimized and resources are maximized. However, a critical aspect of this research highlights a significant economic challenge. While the health and environmental benefits are clear, the economic feasibility of this process remains a considerable hurdle. The intensive drying process results in a heavy economic cost, which currently limits the large-scale commercial viability of the product.

1. Introduction

The contemporary food sector is characterized by a dynamic transformation, driven by a growing imperative towards circular and sustainable food systems.[1] In this framework, the development of plant-based meat analogues, such as vegan burgers, represents not only a response to shifting consumer diets but, more importantly a strategic opportunity to reduce the environmental pressure associated with traditional livestock production. From a comparative perspective, while traditional meat burgers are established staples in global diets, their production is increasingly scrutinized for its high environmental pressure and associated health risks, such as high saturated fat intake. Consequently, the market is no longer restricted to strict vegans or vegetarians but is increasingly dominated by "flexitarian" consumers seeking to reduce meat consumption for ethical, environmental, and health reasons. However, these consumer levels demand products that provide a comparable gastronomic experience without compromising the nutritional robustness typically expected from plant-based whole foods. The formulation of these products presents inherent challenges related to the need to faithfully replicate

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critical organoleptic attributes such as texture, consistency, and cohesion, while maintaining a high nutritional value.[2] However, it's crucial to acknowledge that many of these next-generation plant-based analogues, especially vegan burgers, often lack sufficient dietary fibers compared to whole plant-based foods or even traditional meat products supplemented with fiber-rich ingredients. While they often reduce cholesterol and saturated fats, several studies indicate that the processing involved in creating these analogues can significantly diminish their natural fiber content, a critical component for digestive health and satiety.[3,4] This can result in products that, despite being plant-based, are less nutritionally robust in terms of fiber than what consumers might expect from a diet rich in vegetables, legumes, and whole grains. These considerations underscore the importance of exploring strategies to enrich the intrinsic nutritional profile of these products, particularly regarding their fiber content.

The management of horticultural by-products presents both a substantial environmental challenge and a strategic opportunity for value creation within the agro-industrial sector. Global horticulture production generates a significant volume of by-products, with fruit and vegetable waste, reaching approximately 175 million tonnes annually. This represents a critical scenario where up to 60% of total production can be lost or wasted throughout the supply chain. The by-products, traditionally considered waste streams, are concentrated sources of dietary fibers and bioactive compounds.[5–8] The production trends for specific components selected in this study confirm this abundance: artichoke processing generates waste (bracts and stems) accounting for 60–80% of the plant's weight, while prickly pear peels constitute about 40% of the fruit. Similarly, broccoli and carrots contribute significant residual biomass, stems and peels, often representing 25–30% of the raw material.[9] The innovative approach lies precisely in the valorization of residual horticultural matrices, transforming these environmental burdens into valuable resources for the functional enrichment of vegan burgers. This strategy not only mitigates the prevalent fiber deficiency in Western diets[10] but also represents a significant advancement toward circular food production. By conferring multifunctional added value that transcends mere fiber supplementation to encompass functional, technological, and economic benefits, this integration could actively align with circular economy principles and foster a resilient food future.

A significant gap in the current literature pertains to the direct and comprehensive investigation of employing horticultural by-products specifically to supplement the deficient fiber content in vegan burgers. While studies address the general valorization of these by-products[11] and the fiber shortcomings of plant-based analogues, research specifically focusing on this targeted application remains very scarce. Each by-product matrix, by virtue of its unique phytochemical and structural composition, contributes specifically to enhancing the product's properties, with a particular emphasis on its nutritional attributes. While the broader potential of horticultural by-products is well-documented,[12–14] this study specifically investigates the valorization of prickly pear peels, carrot by-products, broccoli by-products, turnip tops by-products, and artichoke by-products. These matrices were selected due to their distinct phytochemical and structural compositions, which promise to address the identified nutritional and technological challenges in vegan burger formulations. Prickly pear peel was included for its notable content of soluble fibers and phenolic compounds, which can improve the texture and antioxidant profile.[15] Carrot by-products offer a rich source of carotenoids and fibers, ideal for enriching the nutritional value and chromatic appeal of formulations.[16] Broccoli by-products were selected for their contribution of glucosinolates and fibers, contributing to nutraceutical properties and a more cohesive structure.[17] Turnip top by-products were chosen for their unique profile of vitamins and bioactive compounds, which can impart distinctive flavors and health benefits.[18] Finally, artichoke by-products were included for their high content of inulin and bitter compounds, capable of positively influencing consistency and prebiotic properties.[19]

In light of the challenges and opportunities outlined, this study aims to evaluate the sustainability and functional potential of vegan burgers enriched with the horticultural by-products described herein, with a primary focus on carbon footprint reduction[20] and nutritional fortification. Our objective is to demonstrate how the integration of these by-products can address the fiber deficiency typical of many meat analogues while enhancing their antioxidant properties. To ensure the technological feasibility and consumer viability of these sustainable formulations, sensory analysis was employed as a supporting tool to validate that the environmental and functional improvements meet acceptability standards. This approach seeks to define an innovative pathway for developing more complete, palatable, and environmentally friendly plant-based foods.

2. Materials and methods

2.1. By-product processing

The fruit and vegetable raw materials were supplied by local companies in Foggia (Apulia, Italy) and transported to the laboratory. Upon arrival, all materials were stored at 4 °C until processing. The raw materials were thoroughly washed with water, immersed in a 20 mL L^{-1} sodium hypochlorite solution for 5 min, rinsed, and allowed to air dry. Red prickly pears (*Opuntia ficus-indica* L. Mill., Sanguigna cultivar) and carrots (*Daucus carota*) were subsequently peeled and cut. Broccoli by-products (*Brassica oleracea* var. *italica*), artichoke by-products (*Cynara cardunculus* var. *scolymus*), and turnip top by-products (*Brassica rapa* var. *cymosa*) were directly cut after the washing and drying steps. For dehydration, a conventional dryer (PF-SIC CO80PRO, SICCOTECH, Campobasso, Italy) was adopted. Drying was performed using a hot air process with natural convection at ambient pressure. The dryer is a cabinet with a volume of 0.6 m^3, equipped with 20 racks (72 × 53 × 3 cm). The process was carried out at a specific drying temperature of 60 °C; during the dehydration, the relative humidity (RH) inside the cabinet was monitored, reaching a stable value of approximately 5%. To ensure precise drying, periodic measurements of moisture content were performed on 5 g samples using a moisture analyzer (Sartorius, Göttingen, Germany) set at 130 °C. Drying was stopped when the moisture value remained stable for 2–3 consecutive measurements. Following drying, the dehydrated by-products were ground using a laboratory grinder (Sanven Technology Ltd., distributor for the Vevor brand, Rancho Cucamonga, California, USA) to obtain a fine powder with a particle size of around 500 μm. The resulting powders were stored under vacuum at refrigeration temperature (approximately 4 °C) until further analyses.

2.2. Vegan burger preparation

All ingredients used for the vegan burger preparation were purchased from a local supermarket (Foggia, Apulia, Italy). Six different burger formulations were prepared: one control burger and five experimental burgers incorporating the various by-products (CP, TT, BB, AB, and PPP). For the control burger (CTRL), all the ingredients were bought fresh. The fresh ingredients, carrots, onion, and parsley, were thoroughly washed and cut before being added to a laboratory mixer. Canned borlotti beans were drained and rinsed thoroughly before use. The ingredients were added to the mixer in this order for an initial coarse grind: onion, carrots, parsley, oil, and salt, following the proportions reported in Table 1. After that, the prepared borlotti beans were added, followed by a second grind to get a uniform mixture. Finally, potato flakes were mixed in, and the mixture was ground one last time. The resulting dough was then manually mixed, pressed using a manual press (Beckers, Treviglio, Italy), and subsequently baked in an oven (Bimar, Sirmione, Italy) at 180 °C for 10 min.

The by-product vegan burger preparation largely mirrored the control burger procedure, with the pre-hydrated by-product powder (for approximately 30 min) incorporated as the final ingredient. The by-product inclusion was optimized by incrementally increasing its mass fraction (see Table 1) until the overall quality of the burger met a minimum score of 6 to 7 for the cooked product. The specific quantity of water employed for pre-hydrating the by-product was selected to mitigate any adverse effects on the burger's sensory attributes; detailed data concerning this optimization are not presented here. The variation in the mass fractions of secondary ingredients (such as beans and water) across the different formulations was necessary to compensate for the diverse water-holding capacities and structural differences of each horticultural by-product. This adjustment was essential to maintain the technological consistency and structural integrity of the dough, ensuring that all fortified burgers achieved a comparable texture and met the minimum sensory acceptability threshold.

Table 1 Mass fraction of ingredients for the control and fortified vegan burger formulations[a]

Ingredients	CTRL	CP	TT	BB	AB	PPP
Beans	0.5965	0.5443	0.5327	0.3730	0.5513	0.4219
Carrot	0.1438	0.0000	0.1284	0.0899	0.1329	0.1017
Onion	0.0666	0.0608	0.0595	0.0416	0.0615	0.0471
Parsley	0.0024	0.0022	0.0021	0.0015	0.0022	0.0017
Salt	0.0096	0.0087	0.0086	0.0060	0.0089	0.0147
Oil	0.0240	0.0219	0.0214	0.0150	0.0222	0.0170
Water	0.0000	0.0972	0.0713	0.2498	0.0413	0.1266
By-product	0.0000	0.1215	0.0357	0.1249	0.0345	0.1582
Potato flake	0.1571	0.1434	0.1403	0.0983	0.1452	0.1111

[a] CTRL: control sample; CP: burger with carrot peel; TT: burger with turnip top by-products; BB: burger with broccoli by-products; AB: burger with artichoke by-products; PPP: burger with prickly pear peels.

2.3. Chemical analyses

All chemicals and reagents were obtained from Sigma-Aldrich (Milan, Italy) and were of analytical grade. These included Folin–Ciocalteu reagent (2.0 N), gallic acid monohydrate (MW: 188.3 g mol^{-1}, purity ≥ 98.0%), anhydrous sodium carbonate (MW: 105.99 g mol^{-1}, purity ≥ 99.5%), methanol (purity ≥ 99.8%), hydrochloric acid, 2,2-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)diammonium salt (ABTS) (MW: 548.68 g mol^{-1}, purity ≥ 98%), sodium acetate buffer solution, potassium persulfate (MW: 270.35 g mol^{-1}, purity ≥ 99%), Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid) (MW: 250.29 g mol^{-1}, purity ≥ 97%), aluminum chloride (MW: 133.34 g mol^{-1}, purity 99%), sodium nitrite (MW: 69.00 g mol^{-1}, purity ≥ 97%), sodium hydroxide solution (purity ≥ 99%) and quercetin (MW: 302.24 g mol^{-1}, purity ≥ 95%). Anhydrous sodium carbonate was supplied by Carlo Erba (Milan, Italy). For the analyses, sample extraction was performed using a modified protocol based on the method of Panza *et al.*[21] In brief, all samples were initially dried in a laboratory oven at 35 °C, and then ground into a fine powder. Two grams of each dried sample were combined with 20 mL of acidified methanol 80% MeOH in water, and acidified with 1% HCl. The resulting mixture then underwent ultrasonication at 60 °C for 30 min at 80% ultrasonic power using a laboratory ultrasonic bath (CP104, CEIA, Viciomaggio, Italy). Following ultrasonication, the samples were centrifuged at 4 °C for 10 min at 10.000 rpm (5804R, Eppendorf, Milan, Italy) to isolate the supernatant. All extraction procedures were carried out in triplicate.

The total phenolic content (TPC) was determined using the colorimetric Folin-Ciocalteu method, as previously reported in ref. 21. TPC values are expressed as milligrams of gallic acid equivalents (GAE) per g dry weight (dw), quantified against a gallic acid calibration curve (3.12–100 mg L^{-1}; $R^2 = 0.999$). The total flavonoid content (TFC) was assessed using the aluminum chloride colorimetric method, consistent with the procedure described by Cedola *et al.*[22] TFC results are presented as milligrams of quercetin equivalents (QE) per g dw derived from a quercetin calibration curve (6.25–400 mg L^{-1}; $R^2 = 0.995$).

The antioxidant activity of the vegan burger was evaluated using both the ABTS (2,2-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt) and FRAP (Ferric Reducing Antioxidant Power) assays. The ABTS assay was performed according to the methodology outlined by Cedola *et al.*[22] A calibration curve was established using Trolox as a standard over a concentration range of 12.5 to 500 mg L^{-1} ($R^2 = 0.990$). Antioxidant activity was reported as milligrams of Trolox equivalents per g dw. The FRAP assay was also conducted following the procedure detailed by Marinelli *et al.*[23] Antioxidant activity was expressed as millimoles of ferrous equivalents Fe(II) per g dw. A calibration curve was generated using ferrous sulfate heptahydrate as a standard, with concentrations ranging from 0.1 to 0.8 mmol L^{-1} ($R^2 = 0.993$). The antioxidant capacity was additionally expressed as μmol of ferric equivalents Fe(II) per g dw.

2.4. Total dietary fiber content

Both raw materials and all the vegan burger samples were analyzed for Total Dietary Fiber (TDF) using the AOAC Official Method[24] and expressed in g per 100 g. The analysis was conducted at the NIRO SRL private laboratory located in Campobasso (CB), Italy.

2.5. Environmental impact

Life Cycle Assessment (LCA) is described as a structured method used to assess industrial activities and products by analyzing the consumption of energy and raw materials, emissions to the environment, and identifying options for reducing environmental impacts.[26] The LCA methodology adopted in this study followed the guidelines set by the International Organization for Standardization (ISO) and comprised the following phases: goal and scope definition, inventory analysis, impact assessment, and interpretation of results.[27] All activities and associated environmental impacts occurring before the generation of biowaste were excluded from the analysis, as the various by-products considered in this study were classified as 'burden-free'. The functional unit (FU) quantitatively expresses the function of the product system, providing a standardized reference for the normalization and comparison of all input and output flows within the system boundaries.[28] In this study, the FU was defined as 1 kg of vegan burgers. The complete supply chain was analyzed for all ingredients, excluding only the by-products employed in the vegan burger production process. The environmental impact data, in terms of the carbon footprint, for the various ingredients used in the preparation of the vegan burgers were extracted from different sources, as detailed in the SI (Table S1). Primary data directly obtained from the laboratory of the University of Foggia were employed to characterize the recycling process, with a specific focus on quantifying the energy demand associated with the dehydration and grinding stage of the by-products. A quantitative assessment of the contributions of inventory-stage inputs and outputs to the predefined environmental impact categories was conducted as part of the life cycle assessment. The analysis applied the "CML-IA baseline v3.06" method implemented in the SimaPro software, version 9.6.0.1, to estimate potential impacts. The assessment specifically focused on the Global Warming Potential (GWP100) indicator, reported in kilograms of CO_2 equivalent ($kgCO_2eq$).

2.6. Sensory analysis

Sensory evaluation of the vegan burger samples was conducted by a panel of seven experienced female assessors (PhD students and researchers), from the University of Foggia's Food Science Department, aged between 25 and 50 years. The choice of an all-female panel was based on the internal composition of the research laboratory and is supported by several studies indicating that women often demonstrate higher acuity and more consistent performance in Quantitative Descriptive Analysis (QDA) than men.[25] Although the panelists had prior experience in food sensory analysis, they underwent two dedicated retraining sessions, each lasting two hours. During these sessions, commercial vegan burgers were used to standardize evaluation parameters and ensure panelist alignment for the Quantitative Descriptive Analysis (QDA) method. This method quantified the intensity of specific sensory attributes for both raw and cooked samples. For raw burgers, panelists evaluated color, odor, appearance, and texture. For cooked samples, additional attributes assessed included color, odor, appearance, texture, chewiness, grittiness, and taste. Each panelist also provided an overall sensory quality score for both raw and cooked burgers. A 9-point intensity scale was utilized for scoring each specific sensory attribute and the overall sensory quality, where 1 represented the lowest score and 9 represented the highest. A score of 5 was established as the acceptability threshold. The evaluation form is reported in the SI (Table 2). Samples were presented randomly on white plates in a controlled sensory evaluation environment. Water and plain crackers were provided between samples to cleanse the palate. The raw and cooked vegan burgers used in this assessment were prepared with quality ingredients under appropriate hygienic practices. Prior to participation, panelists provided informed written consent, which detailed the study's objectives and data privacy policies, and confirmed that the burgers were prepared following hygiene standards. Participants were also informed of any potential risks, which were deemed negligible for this study.

2.7. Statistical analysis

Statistical analysis was performed using JMP Student Edition 18 (SAS Institute Inc., Cary, NC, USA). One-way analysis of variance (ANOVA) was conducted, followed by the Student's *t*-test with the option for homogeneous groups ($p < 0.05$), to determine significant differences among the evaluated parameters.

3. Results and discussion

Our results provide critical insights into how the inclusion of these sustainable ingredients impacts key sensory characteristics, for both raw and cooked products. Furthermore, this work evaluates enhanced nutritional properties of the developed formulations. Finally, the study addressed the environmental impact of production.

3.1. Sensory quality of vegan burgers

Table 2 presents the overall quality values for both raw and cooked burgers. As indicated by the data, the limiting overall quality (*i.e.*, the lower score) consistently corresponded to the cooked burger. Consequently, the cooked burger's overall quality will serve as the primary sensory attribute for further analysis. Regarding the cooked burgers, the inclusion of the by-

Table 2 Overall quality of raw and cooked burgers with and without by-products[a]

Sample	Overall quality: Raw burgers	Cooked burgers
CTRL	8.8 ± 0.26[a]	8.7 ± 0.26[a]
CP	6.7 ± 0.41[c]	6.6 ± 0.58[b]
TT	8.5 ± 0.0[b]	6.6 ± 0.22[b]
BB	8.1 ± 0.25[b]	6.5 ± 0.41[b]
AB	8.3 ± 0.27[b]	6 ± 0.0[b]
PPP	8.5 ± 0.0[b]	6.2 ± 0.27[b]

[a] Data in each column with different letters are statistically different ($p < 0.05$). CTRL: control sample; CP: burger with carrot peel; TT: burger with turnip top by-products; BB: burger with broccoli by-products; AB: burger with artichoke by-products; PPP: burger with prickly pear peels.

products, as anticipated, led to a decrease across all sensory attributes. The trained panel observed that for CP (Carrot Peels) and BB (broccoli), the main impact was on color (more intense hues) and a slight increase in fibrousness. For TT (Turnip Tops) and AB (artichoke), the decline in overall quality was primarily driven by the emergence of bitter notes and strong characteristic aromas that partially masked the bean base. In the case of PPP (prickly pear), the texture remained more cohesive, explaining its higher acceptability despite the high inclusion rate. This finding is consistent with various studies that report challenges in maintaining sensory parity when incorporating high levels of fiber-rich by-products or novel ingredients into food matrices. Such challenges often arise due to changes in texture, color, and particularly the flavor profile.[29,30] For instance, research by Gómez *et al.*[31] on incorporating fruit by-products into baked goods noted similar reductions in overall sensory acceptance, often attributed to altered textural perceptions and introduction of new flavor notes. Similarly, findings by Socas-Rodríguez *et al.*[32] on vegetable waste incorporation in food products highlighted that while nutritional value improved, sensory attributes, especially taste and appearance, frequently experienced a decline. Among these, taste was the most significantly impacted attribute.[33] The inherent flavors or slight bitterness/earthiness of certain by-products can often become more pronounced after cooking, negatively influencing the perceived taste of the final product, as demonstrated in studies evaluating plant-based protein sources and their impact on flavor.[34]

As reported beforehand, Table 1 presents the mass fraction of each by-product utilized for the burger fortification. Interestingly, data suggest an inverse relationship: a greater mass fraction of the by-product is correlated with a lower sensory impact. By combining the information from Tables 1 and 2, it can be inferred that prickly pear peel had the least impact on the sensory quality of vegan burgers. Carrots and broccoli followed, with turnip top and artichoke by-products having the most significant sensory impact. This observation, where different by-products exert varying degrees of sensory influence, is well-documented in food science literature. The specific chemical composition of each by-product, including its fiber content, pigment compounds, and volatile aromatic agents, plays a crucial role in its sensory footprint.[35] For instance, prickly pear peels, often valued for their mild flavor and high fiber content, may integrate more seamlessly into food matrices without imparting strong off-notes.[36] This aligns with our finding that they had the least sensory impact, even at potentially higher inclusion rates. Conversely, by-products like turnip tops and artichokes are known to contain more pronounced bitter compounds or strong characteristic flavors that can negatively affect the overall taste and aroma of a finished product when incorporated at high levels.[37,38] This often necessitates careful optimization of their inclusion levels or specific pre-treatments to mitigate undesirable sensory effects, a challenge frequently reported in the development of fortified food products using diverse vegetable waste. Our results for carrots and broccoli falling in between suggest a moderate sensory impact, likely due to their less intense inherent flavors compared to turnip tops and artichokes, but still contributing distinct notes that require consideration.

3.2. Bioactive compounds and antioxidant capacity of vegan burgers

This study analyzed the primary nutritional indices of several by-products from artichoke, prickly pear, turnip tops, carrots, and broccoli. We incorporated these into vegan burgers to evaluate their enhanced nutritional profiles compared to a control sample. Table 3 details the main nutritional indices of the by-products used in this study, including their antioxidant activity as measured by ABTS and FRAP assays. It's important to

Table 3 Total phenol content, total flavonoids, and antioxidant activity by ABTS and FRAP assays, and total dietary fiber (TDF) contents of by-products from different sources[a]

By-products	Total phenols (mg GAE per g dw)	Total flavonoids (mg QE per g dw)	FRAP (μmol Fe(II) per g dw)	ABTS (mg Trolox per g dw)	TDF (g per 100 g)
Prickly pear	9.20 ± 0.11[a]	4.83 ± 0.73[b]	65.03 ± 1.43[b]	6.57 ± 0.01[a]	31.1 ± 1.79[c]
Turnip tops	8.15 ± 0.09[b]	7.33 ± 0.39[a]	79.24 ± 0.67[a]	6.56 ± 0.01[a]	28.4 ± 1.63[c]
Broccoli	2.82 ± 0.10[d]	2.07 ± 0.26[c]	52.20 ± 0.84[d]	4.69 ± 0.06[c]	38.9 ± 2.24[b]
Carrot	2.25 ± 0.04[e]	2.18 ± 0.24[c]	56.60 ± 0.84[c]	4.93 ± 0.05[b]	24.1 ± 0.27[d]
Artichoke	6.82 ± 0.19[c]	7.90 ± 0.47[a]	56.45 ± 0.23[c]	6.58 ± 0.01[a]	43 ± 2.47[a]

[a] Data in each column with different letters are statistically different ($p < 0.05$).

Table 4 Total phenol content, total flavonoids, and antioxidant activity by ABTS and FRAP assays, and total dietary fiber (TDF) of vegan burgers with and without by-products from different sources[a]

Sample with by-products	Total phenols (mg GAE per g dw)	Total flavonoids (mg QE per g dw)	FRAP (μmol Fe(II) per g dw)	ABTS (mg Trolox per g dw)	TDF (mg g^{-1} dw)
CTRL	0.85 ± 0.04^{d}	0.84 ± 0.05^{d}	16.28 ± 0.07^{d}	2.31 ± 0.10^{e}	5.9 ± 0.35^{d}
PPP	2.11 ± 0.17^{a}	$1.46 \pm 0.12^{b,c}$	24.14 ± 1.43^{a}	5.40 ± 0.19^{a}	10.5 ± 0.61^{a}
TT	$1.10 \pm 0.05^{c,d}$	1.61 ± 0.06^{b}	18.85 ± 1.37^{c}	3.07 ± 0.24^{c}	7.3 ± 0.43^{c}
BB	1.17 ± 0.05^{c}	$1.51 \pm 0.08^{b,c}$	$17.84 \pm 0.8^{c,d}$	$2.79 \pm 0.06^{c,d}$	8.7 ± 0.51^{b}
CP	1.42 ± 0.02^{b}	2.12 ± 0.10^{a}	21.60 ± 0.61^{b}	3.54 ± 0.17^{b}	9.1 ± 0.53^{b}
AB	$0.98 \pm 0.18^{c,d}$	1.31 ± 0.19^{c}	20.62 ± 0.27^{b}	$2.63 \pm 0.07^{d,e}$	7.7 ± 0.45^{c}

[a] Data in each column with different letters are statistically different ($p < 0.05$). CTRL: control sample; CP: burger with carrot peel; TT: burger with turnip top by-products; BB: burger with broccoli by-products; AB: burger with artichoke by-products; PPP: burger with prickly pear peels.

note that there isn't a complete correspondence between the FRAP and ABTS values for the by-products, a common phenomenon in food science. When ABTS is used, the by-products with the highest antioxidant activity are artichoke, prickly pear peel, and turnip tops, with no statistically significant differences among them ($p > 0.05$), followed by carrots, and then broccoli. However, this order changes when FRAP is considered. In this case, turnip tops exhibit the highest value, followed by prickly pear peel, then carrots and artichoke, with no statistically significant difference between them ($p > 0.05$), and finally broccoli. This lack of complete correspondence is expected because FRAP and ABTS assays quantify antioxidant potential through distinct mechanisms. The FRAP assay primarily measures a sample's capacity to reduce ferric tripyridyltriazine ($Fe3^{+}$-TPTZ) to ferrous tripyridyltriazine ($Fe2^{+}$-TPTZ) under acidic conditions, reflecting the reducing power of the antioxidants present. Conversely, the ABTS assay assesses the ability of antioxidants to scavenge the $ABTS^{\cdot}+$ radical cation, indicating their radical-scavenging efficiency.[39] Factors influencing these disparate rankings include reaction kinetics, pH sensitivity, and solubility characteristics of the antioxidants within the sample.[40] For instance, compounds with strong reducing power might show higher FRAP values, while those more effective at scavenging free radicals might exhibit higher ABTS values. Therefore, FRAP and ABTS values often provide complementary yet non-concordant insights into a sample's comprehensive antioxidant profile. Similarly, there isn't a complete correspondence between the total phenol content of the investigated by-products and their antioxidant activity (both FRAP and ABTS). The by-product with the highest phenol content is prickly pear peel, followed by turnip tops, artichoke, broccoli, and finally carrot by-products. This decreasing order is not consistently observed for either ABTS or FRAP values. The absence of a direct correlation between total phenol content and antioxidant activity is another recurring observation in the literature. While phenolic compounds are well-known for their significant antioxidant properties, they do not exclusively dictate a sample's overall antioxidant capacity. Other bioactive compounds, including vitamins (*e.g.*, ascorbic acid and tocopherols), carotenoids, and specific peptides, can also contribute substantially to the total antioxidant potential.[41] Furthermore, total phenol content measurements quantify the aggregate sum of all phenolic compounds without accounting for their individual antioxidant potencies or bioavailability. The actual antioxidant activity, conversely, reflects the cumulative effect of all compounds capable of exerting antioxidant effects under specific assay conditions. The chemical structure, specific type, concentration, and synergistic interactions among diverse phenolic compounds, as well as their interplay with non-phenolic antioxidants, profoundly influence the ultimate antioxidant outcome.[42] Consequently, a higher total phenol content doesn't necessarily translate into a proportionally higher antioxidant activity, thus explaining the observed analytical discrepancies.

Flavonoids, a broadly defined group of polyphenolic compounds, represent a pivotal class of secondary metabolites in plants, lauded for their potent antioxidant, anti-inflammatory, and anti-carcinogenic properties. As shown in Table 3, artichoke and turnip top by-products displayed the highest total flavonoid content, suggesting a significant contribution to the antioxidant potential through these specific compounds.

Dietary fibers constitute a crucial component of plant-based matrices, playing a fundamental role in human physiological well-being through their diverse impacts. The by-products incorporated in this study, particularly those originating from vegetables and fruits, are anticipated to serve as rich reservoirs of diverse fiber types, thereby substantially enriching the nutritional profile of the resulting vegan burgers. As evidenced by the Total Dietary Fiber (TDF) values presented in Table 3, a significant variability in fiber content exists among the selected by-products, underscoring their potential for targeted applications. Artichoke by-products exhibited the highest TDF content, with a value of 43 ± 2.47 g per 100 g, indicating their superior fiber-donating capacity. This is followed closely by broccoli by-products, which also demonstrated a high TDF of 38.9 ± 2.24 g per 100 g. These findings are statistically distinct, highlighting the significant differences in fiber concentration among these sources ($p < 0.05$). Prickly pear peel (31.1 ± 1.79 g per 100 g) and turnip top by-products (28.4 ± 1.63 g per 100 g) also represent valuable sources of dietary fiber, though their levels are statistically lower than those of artichoke and broccoli residues ($p < 0.05$). The lowest TDF value among the tested samples was observed in carrot by-products, at 24.1 ± 0.27 g per 100 g, yet still indicating a notable contribution. The strategic inclusion of these fiber-rich by-products not only contributes favourably to the textural characteristics of the food product, potentially acting as natural binding agents and improving mouthfeel, but also significantly enhances its overall dietary fiber content.

As Table 4 clearly shows, all the fortified burgers have higher ABTS and FRAP values than the control. This indicates that, even when added in minimal quantities due to their strong impact on sensory quality, all the investigated by-products improve the antioxidant activity of the burger. Data in Table 4 reveal that the burger fortified with prickly pear peel registered the highest ABTS value, followed by the burger fortified with carrot, and finally with turnip top, broccoli, and artichoke by-products ($p > 0.05$). As observed with the by-products themselves, a complete correspondence between the ABTS and FRAP values in the fortified burgers was not found. The same underlying reasons previously discussed for the by-products, such as differing mechanisms of action of the assays (radical scavenging *vs.* reducing power) and the varied chemical structures of antioxidant compounds, apply to the fortified burger formulations.[39,40] The literature offers numerous comparisons of antioxidant activity in various food products, sometimes utilizing the same by-products or the same food fortified with different waste materials. For example, studies on bread fortified with fruit and vegetable by-products have shown similar increases in antioxidant capacity, often correlating with the initial antioxidant richness of the added material.[43,44] These findings consistently support the notion that even minimal additions of antioxidant-rich plant waste can significantly enhance the functional properties of food products. As can be observed from data shown in Table 4, the total phenol content of the investigated fortified burgers does not match completely with the values of their ABTS and FRAP activities. As observed above, this discrepancy may be attributed to a combination of specific biochemical and methodological factors. First, the drying process at 35 °C can cause the partial degradation of some thermolabile phenols while simultaneously promoting the release of bound phenolic compounds from the fiber-rich cell wall of artichoke and prickly pear, which might respond differently to various assays. The total phenol measurement quantifies all phenolic compounds irrespective of their individual antioxidant efficacy or bioavailability within the complex food matrix.[42] Moreover, the Folin-Ciocalteu reagent is known to react with non-phenolic reducing substances, such as reducing sugars or organic acids released during the sample preparation, which may overestimate the TPC value. Additionally, other non-phenolic compounds contribute to overall antioxidant activity, and complex interactions (synergistic, additive, or antagonistic) between different constituents within the burger can influence the final antioxidant capacity.[41]

The antioxidant activity of the fortified burger is partly related to the intrinsic characteristics of the by-product used for fortification and partly to its weight fraction in the final product. Multiplying the antioxidant activity of the by-product by its weight fraction provides a rough estimate of the by-product's potential contribution to the fortified burger's antioxidant activity, assuming linear sum ability of individual constituents' effects. In other words, this assumes the burger behaves as an ideal mixture, where interactions between different components are negligible and similar to those between components of the same species (*i.e.*, the theory of ideal mixtures).

Fig. 1 shows FRAP and ABTS values as a function of the by-product mass fraction, respectively. In the figure, prickly pear peel is the by-product that contributed most significantly to the antioxidant activity of the fortified burger, followed closely by broccoli and carrot by-products, and finally artichoke and turnip top by-products. To facilitate a proper comparison between these assays, it should be noted that while ABTS evaluates the free radical scavenging capacity, the FRAP assay specifically quantifies the ferric reducing antioxidant powder (reflecting a Single Electron Transfer – SET mechanism). As for the prickly pear peel, all indicators of antioxidant activity (ABTS and FRAP, chose to represent both radical scavenging and reducing power) reach their maximum value in the burger enriched with this by-product. The result is not unexpected, considering that this by-product has both the highest mass fraction among the studied by-products and one of the highest inherent antioxidant activities. Regarding the other by-products, there isn't a complete correspondence between the contributions estimated in Fig. 1 and the observed data listed in Table 4. The reasons for this discrepancy are multifaceted. Primarily, the burger matrix likely does not behave as an ideal

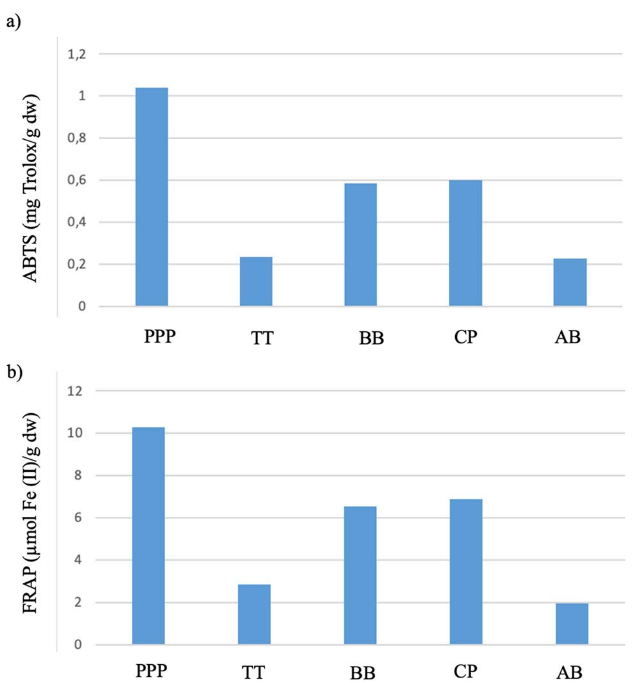

Fig. 1 Antioxidant activity by (a) ABTS and (b) FRAP assays of vegan burgers. PPP: burger with prickly pear peels; TT: burger with turnip top by-products; BB: burger with broccoli by-products; CP: burger with carrot peel; AB: burger with artichoke by-products.

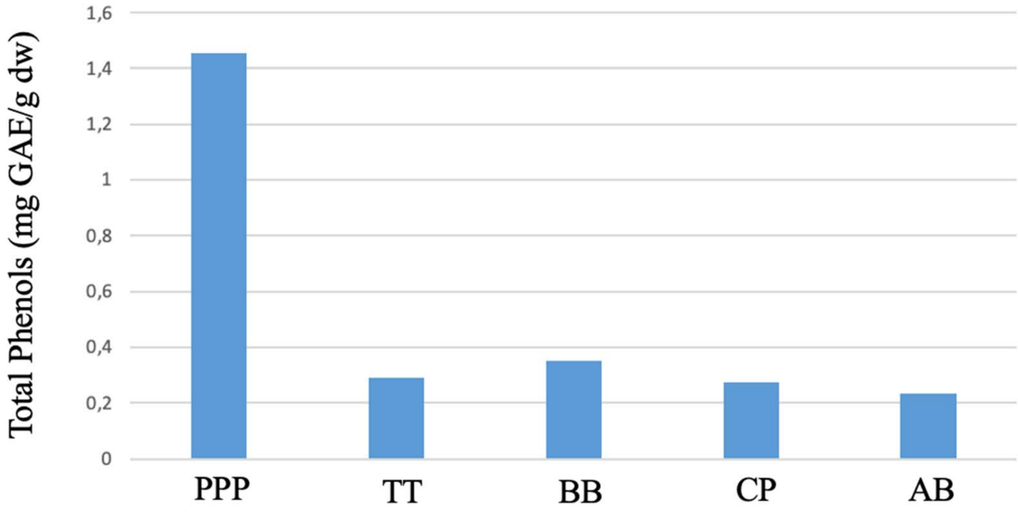

Fig. 2 Total phenols (mg GAE per g dw) of different vegan burgers. PPP: burger with prickly pear peels; TT: burger with turnip top by-products; BB: burger with broccoli by-products; CP: burger with carrot peel; AB: burger with artichoke by-products.

mixture; that is, the interactions between its various constituents are significant and not negligible. Consequently, interactions among different components may not be equivalent to those between components of the same species. Such non-ideal behavior in complex food systems is widely documented in the literature.[45,46] In addition to the non-ideal mixture behavior, the discrepancy between data reported in Table 4 and those in Fig. 1 could stem from the interaction among the different constituents of the burger, which can lead to the formation of new compounds. These newly formed compounds might possess different antioxidant properties (either enhanced or diminished) compared to their precursors.[47,48] Thermal processing during burger preparation could also induce chemical changes, thus affecting the stability and bioactivity of the antioxidants.

Fig. 2 shows total phenol content as a function of the by-product mass fraction. As previously mentioned, this product provides a rough estimate of the individual by-product's contribution to the total phenol content of the fortified burger, under the assumption that the burger behaves as an ideal mixture. As shown in the figure, prickly pear peels contribute most significantly to the total phenol content among the investigated by-products. This result aligns well with data listed in Table 4. Like the antioxidant activity, this outcome is not unexpected, given that prickly pear peels have both the highest mass fraction and the highest inherent total phenol content. As

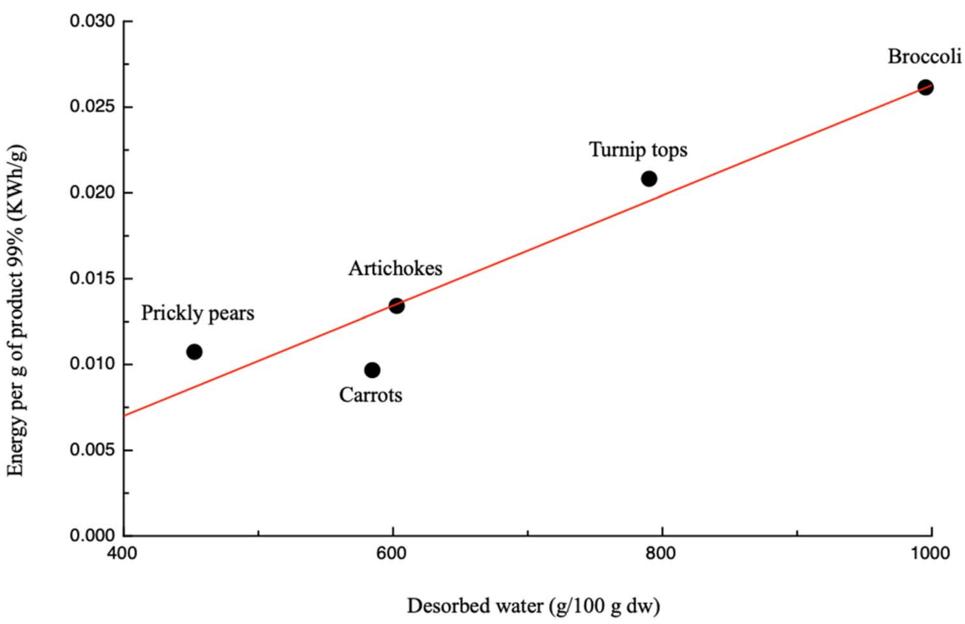

Fig. 3 Energy per g of dried by-products.

Table 5 Energy consumption (kW h g^{-1}) for dehydration and grinding of different by-products

By-products	Dehydration [kW h g^{-1}]	Grinding [kW h g^{-1}]	Total energy [kW h g^{-1}]
Prickly pear	$1.074 \cdot \times 10^{-2}$	$5.298 \cdot \times 10^{-5}$	$1.079 \cdot \times 10^{-2}$
Turnip tops	$2.082 \cdot \times 10^{-2}$	$5.450 \cdot \times 10^{-5}$	$2.087 \cdot \times 10^{-2}$
Broccoli	$2.616 \cdot \times 10^{-2}$	$3.550 \cdot \times 10^{-5}$	$2.620 \cdot \times 10^{-2}$
Carrots	$9.672 \cdot \times 10^{-3}$	$4.440 \cdot \times 10^{-5}$	$9.717 \cdot \times 10^{-3}$
Artichokes	$1.341 \cdot \times 10^{-2}$	$1.107 \cdot \times 10^{-4}$	$1.352 \cdot \times 10^{-2}$

Table 6 Water desorbed at equilibrium for the dehydration of different by-products

By-products	Initial water weight fraction	Final water weight fraction	Water desorbed at equilibrium [g water per 100 g dry]
Prickly pear	0.8176 ± 0.0335	0.1091 ± 0.0178	452.55 ± 2.25
Turnip tops	0.8875 ± 0.0124	0.0611 ± 0.0154	790.145 ± 1.73
Broccoli	0.9082 ± 0.0109	0.0559 ± 0.0119	995.35 ± 1.33
Carrots	0.8552 ± 0.0106	0.0809 ± 0.0164	584.62 ± 1.95
Artichokes	0.8537 ± 0.0297	0.0691 ± 0.0038	602.72 ± 0.44

shown in Fig. 2, artichoke is the by-product that contributes the least to the total phenol content of the fortified burger. This result is mainly attributable to its low mass fraction in the fortified burger. Indeed, artichoke, alongside turnip tops, significantly impacts the sensory quality of the burger, thus limiting its inclusion level. For the other by-products studied, there isn't a direct correspondence between data shown in Fig. 3 and those listed in Table 4. The reasons for this discrepancy could either be that the burger does not behave as an ideal mixture, or that new compounds are formed due to interactions with other components of the burger matrix, as supported by studies on food component interactions.[49,50]

Data presented in Table 4 reveal how fortification impacts the total flavonoid content of the vegan burgers. The control burger showed the lowest flavonoid content, as expected (0.84 ± 0.05 mg QE per g dw). Notably, the carrot by-product fortified burger exhibited the highest total flavonoid content (2.12 ± 0.10 mg QE per g dw), surpassing even the prickly pear peel-fortified burger (1.46 ± 0.12 mg QE per g dw), despite prickly pear peel having a higher total phenol content. This observation underscores that both the concentration of total flavonoids in the by-products (as seen in Table 3) and their specific inclusion levels play crucial roles. Carrots, while not having the highest overall phenolic content, clearly contribute to the flavonoid profile of the fortified burgers.

Comparing these results with the literature on fortified food products provides valuable context. Studies on pasta or bread enriched with various fruit and vegetable by-products often report increases in flavonoid content, aligning with the type and quantity of the added material.[51,52] Research on other food items fortified with similar agro-industrial wastes, like those incorporating berry pomace or citrus peels, similarly indicates that flavonoid enrichment depends on the original flavonoid profile of the waste and its chemical stability during processing.[53] Specifically, our findings regarding flavonoid increases (up to 2.12 mg QE per g) are consistent with recent studies on pork burgers fortified with *Prunus serotina* extracts, which showed a significant improvement in the bioactive profile of the meat matrix.[54] Furthermore, the use of fruit and vegetable by-products to bridge the antioxidant gap in both vegan and animal-origin products has been increasingly documented as an effective strategy for creating functional 'hybrid' or plant-based foods.[55] This suggests that the processing of the vegan burgers might have different effects on the stability or extractability of flavonoids from various by-products, leading to the observed variations in the final product.

Table 4 clearly illustrates the significant impact of fortification on the Total Dietary Fiber (TDF) content of the vegan burgers. The control sample had a TDF of 5.9 ± 0.35%, while all fortified burgers showed significantly higher fiber content. The burger fortified with prickly pear peel registered the highest TDF at 10.5 ± 0.61%, followed by carrot (9.1 ± 0.53%) and broccoli (8.7 ± 0.51%) by-products. Turnip top and artichoke by-products also effectively increased TDF, reaching 7.3 ± 0.43% and 7.7 ± 0.45% respectively. These findings unequivocally confirm the effectiveness of incorporating these by-products as a strategy to enhance the fiber richness of the final product. Comparing these values with existing literature, it's evident that adding vegetable by-products consistently boosts the fiber content of food matrices. For example, studies on the fortification of meat analogues or plant-based burgers with various vegetable pulps or flours frequently report significant increases in TDF, contributing to a more nutritionally complete product.[56,57] Research on the utilization of prickly pear peel, for instance, has repeatedly highlighted its high dietary fiber content, making it an excellent candidate for functional food development.[58] Similarly, the substantial fiber contributions from carrot and broccoli by-products align with established nutritional data for these vegetables.[59] When compared to traditional animal-origin burgers, which are naturally devoid of fiber, our fortified samples (reaching up to 10.5% TDF) represent a significant nutritional advancement. These results are consistent with the findings of Bilek and Turhan[61] who demonstrated that the nutritional status of beef patties could be enhanced by adding plant-based functional ingredients. Furthermore, our TDF levels align with the trend of using antioxidant-rich wastes, such as grape pomace, to improve the healthy profile of protein-rich matrices, as discussed by Turcu *et al.*[60] These comparisons underscore the successful application of these specific by-products to address the rising consumer demand for fiber-enriched food products.

3.3. Energy consumption

Table 5 shows the energy consumption for the production of the investigated by-products. It includes dehydration and grinding. Regarding the amount of energy consumed per gram of dehydrating by-product, the same procedure used by Le Rose *et al.*[62] was used in this work. As can be seen from the data shown in the table, the energy consumed for grinding is negligible when compared to that consumed for dehydration of by-products. Regarding the latter, a marked difference can be noted among the studied by-products. The above differences are mainly due to the time required to dehydrate each individual by-product (data not shown), which in turn is strictly connected to the amount of water desorbed at equilibrium from the by-product.

Table 6 shows the initial and final water weight fractions of each tested by-product, as well as the amount of water desorbed at equilibrium; as can be observed, there is a clear trend that shows the energy consumed for dehydration increase with the increase in the water desorbed at equilibrium from the by-product (Fig. 3).

3.4. Environmental impact

This section reports the environmental impact, quantified as the carbon footprint, for both the control vegan burger and the formulations enhanced with different types of by-products. Fig. 4 depicts the carbon footprint values associated with the production of 1 kg of each vegan burger. As shown in the figure, the CTRL sample exhibits a lower carbon footprint (0.90 kgCO_2eq per FU) compared to all the other formulations enriched with by-products. The carbon footprint values for the five additional formulations are as follows: artichoke by-products (1.02 kgCO_2eq), turnip top by-products (1.10 kgCO_2eq), and carrot peel (1.25 kgCO_2eq), prickly pear peel (1.31 kgCO_2eq), and broccoli by-products (1.85 kgCO_2eq). The values reveal the different contributions of each by-product incorporation to the overall carbon footprint. This outcome can be explained by the reduction in the amounts of specific ingredients (*e.g.*, beans, carrots, and oil), which is actually not enough to offset the additional carbon footprint associated with the recycling process of by-products. Consequently, the enriched formulations result in a higher overall carbon footprint.

This result aligns with previous studies indicating that plant-based products are characterized by inherently low carbon footprints compared to animal-based products.[63,64] In Europe, direct legal restrictions on the consumption of foods associated with high carbon footprints remain limited. Existing regulatory frameworks primarily address production processes, supply chains, product labeling, and public procurement practices, rather than individual dietary behavior. Nevertheless, several European countries have progressively introduced policy

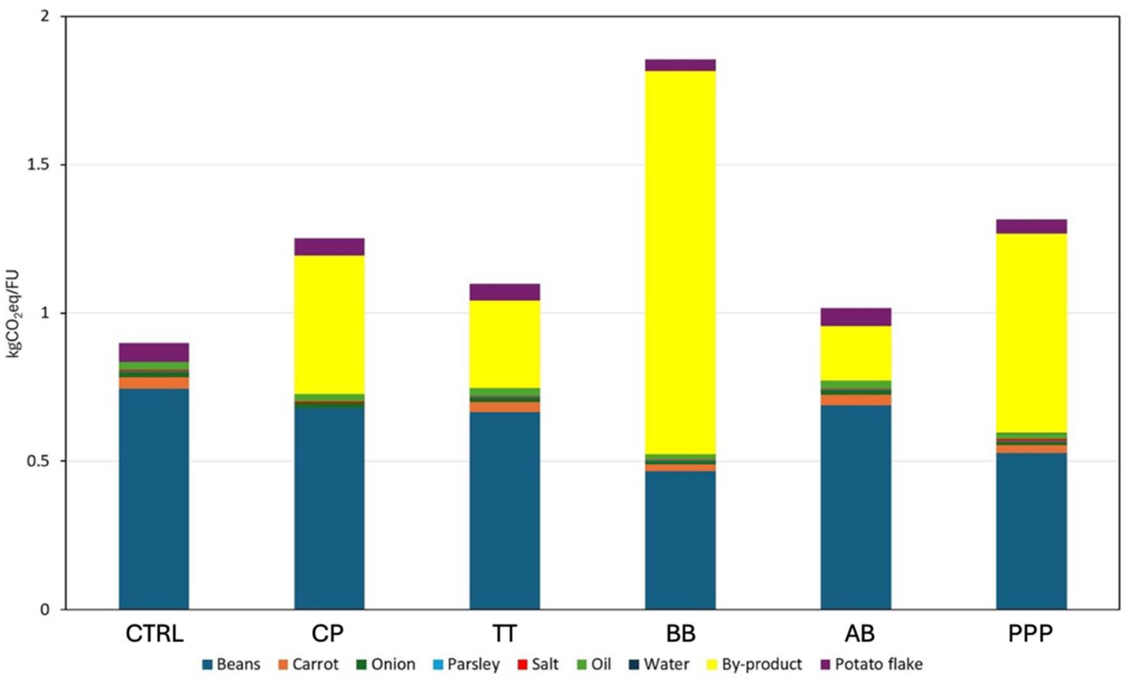

Fig. 4 Carbon footprint of each vegan burger, expressed as kgCO_2eq per kg of product. The contributions of individual ingredients are indicated by different colors. CTRL: control sample; CP: burger with carrot peel; TT: burger with turnip top by-products; BB: burger with broccoli by-products; AB: burger with artichoke by-products; PPP: burger with prickly pear peels.

measures aimed at indirectly influencing consumption patterns. In particular, proposals concerning meat taxation,[65] environmental taxation of dairy products based on associated greenhouse gas emissions,[66] and methane-linked food pricing mechanisms[67] have been explored in several European contexts, although broad consumer-oriented fiscal measures have not yet been widely adopted.

The partial substitution of these ingredients in vegan burger formulations does not entail a significant reduction in their overall carbon footprint (Fig. 4). This result contrasts with other scenarios where ingredients with higher carbon footprints, such as meat, are replaced and result in a substantial decrease in total carbon emissions.[68] It should be noted that among all formulations, the vegan burger enriched with broccoli by-products exhibits the highest carbon footprint. This can be explained by the energy-intensive recycling process required for broccoli residues, which demands 2.7 times more energy than the recycling process of carrot by-products which is the formulation with the lowest energy requirement among all samples. These significant energy requirements contribute to the overall environmental burden of the broccoli related formulation, thus highlighting the importance of considering the energy demand when recycling processes are evaluated.

4. Conclusions

The findings of this study demonstrate the environmental and functional advantages of upcycling horticultural by-products into vegan burgers, contributing to the transition toward circular food systems. Our research successfully validates that these materials, traditionally considered waste, can be transformed into high-value ingredients, directly tackling the issue of food loss while simultaneously reducing the environmental footprint of plant-based meat analogues. The primary contribution of this work lies in the comprehensive assessment of sustainability through Life Cycle Assessment (LCA) and nutritional fortification. The results highlight a significant increase in Total Dietary Fiber (TDF) and antioxidant activity, effectively transferring bioactive compounds from by-products (prickly pear, artichoke, carrot, and broccoli) to the final product. To ensure the technological feasibility and consumer viability of these sustainable formulations, a systematic sensory analysis was conducted. This evaluation confirmed that the environmental and nutritional improvements did not compromise the texture, color, and flavor of the burgers, ensuring their market potential.

This multi-faceted approach confirmed that the valorization of industrial by-products can contribute significantly to the creation of healthier and more sustainable food options. The study successfully establishes a proof of concept for a circular economy model within the food industry, where waste is minimized and resources are maximized. However, a critical aspect of this research highlights a significant economic challenge. While the health and environmental benefits are clear, the economic feasibility of this process remains a considerable hurdle. The high water content inherent in fruit and vegetable by-products necessitates a substantial energy expenditure for drying and subsequent milling to obtain the fine powder required for the formulations. This intensive drying process results in a heavy economic cost, which currently limits the large-scale commercial viability of the product. The energy consumption and the associated costs must be significantly reduced to make this innovative upcycling process economically competitive with traditional ingredients.

In conclusion, this study validates the potential of using agri-food by-products to fortify vegan burgers, offering clear advantages in terms of nutritional value, antioxidant activity, and environmental sustainability. While our findings confirm that this valorization strategy is a promising direction for the future of food production, the economic viability of the process requires further investigation and optimization. Future research should focus on developing more energy-efficient dehydration methods and exploring alternative valorization pathways to reduce production costs, thereby paving the way for the widespread adoption of this circular food innovation.

Institutional review board statement

The current study was classified as exempt from formal Institutional Ethics Committee review, given that the samples were prepared following Good Manufacturing Practices (GMP) and contained no ingredients posing known risk. Regardless, we could also certify and guarantee the following aspects: Food Safety Legislation—all food handling and preparation adhered to the fundamental principles of EU food legislation, specifically Regulation (EC) No 178/2002 (General Food Law) and Regulation (EC) No 852/2004 (on the hygiene of foodstuffs). Food Preparation—all samples were prepared, handled, and cooked in a dedicated food preparation laboratory and were subject to rigorous safety checks. Only cooked or processed samples (*i.e.*, subjected to processes that eliminate health risks due to microorganisms) were served. Allergens and Ingredients—each sample was accompanied by a clear ingredient list that indicated the presence of all major allergens as required by Regulation (EU) No 1169/2011 (Food Information to Consumers). Traceability—raw materials and preparation steps were traceable to ensure food integrity.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Author contributions

M. D. F.: formal analysis and writing – original draft; A. L. R.: formal analysis, methodology, software, and writing – original draft; O. P.: formal analysis and writing – original draft; D. C.: conceptualization, data curation, writing – original draft; A. C.: conceptualization, writing – review and editing, and supervision; M. A. D. N.: conceptualization, data curation, 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.

Data availability

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

Supplementary information (SI): Table S1: inventory data and corresponding data sources; Table S2: sensory evaluation form. See DOI: https://doi.org/10.1039/d6fb00032k.

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References

1 D. Tilman and M. Clark, Global diets link environmental sustainability and human health, *Nature*, 2014, **515**(7528), 518–522, DOI: 10.1038/nature13959.
2 Z. C. D. Mercês, N. M. Salvadori, S. M. Evangelista, T. B. Cochlar, A. D. O. Rios and V. R. Oliveira, Hybrid and Plant-Based Burgers: Trends, Challenges, and Physicochemical and Sensory Qualities, *Foods*, 2024, **13**(23), 3855, DOI: 10.3390/foods13233855.
3 M. K. Alessandrini, S. Brown, R. Pombo-Rodrigues, S. Bhageerutty, F. J. He and G. A. MacGregor, Nutritional quality of plant-based meat products available in the UK: a cross-sectional survey, *Nutrients*, 2021, **13**(12), 4225, DOI: 10.3390/nu13124225.
4 D. Bogueva and D. J. McClements, Safety and nutritional risks associated with plant-based meat alternatives, *Sustainability*, 2023, **15**(19), 14336, DOI: 10.3390/su151914336.
5 A. Aït-Kaddour, A. Hassoun, I. Tarchi, M. Loudiyi, O. Boukria, Y. Cahyana, F. Ozogul and K. Khwaldia, Transforming plant-based waste and by-products into valuable products using various "Food Industry 4.0" enabling technologies: a literature review, *Sci. Total Envir.*, 2024, **955**, 176872, DOI: 10.1016/j.scitotenv.2024.176872.
6 S. P. Bangar, V. Chaudhary, P. Kajla, G. Balakrishnan and Y. Phimolsiripol, Strategies for upcycling food waste in the food production and supply chain, *Trends Food Sci. Technol.*, 2024, **143**, 104314, DOI: 10.1016/j.tifs.2023.104314.
7 S. Plakantonaki, I. Roussis, D. Bilalis and G. Priniotakis, Dietary Fiber from Plant-Based Food Wastes: A Comprehensive Approach to Cereal, Fruit, and Vegetable Waste Valorization, *Process*, 2023, **11**(5), 1580, DOI: 10.3390/pr11051580.
8 T. B. Ribeiro, G. B. Voss, M. C. Coelho and M. E. Pintado, Chapter 33 - Food waste and by-product valorization as an integrated approach with zero waste: future challenges, in *Future Foods*, ed. Bhat, R., Academic Press, Amsterdam, Netherlands, 2022, pp. 569–596, DOI: 10.1016/B978-0-323-91001-9.00017-7.
9 FAO, *The State of Food and Agriculture 2019. Moving Forward on Food Loss and Waste Reduction*, Rome, 2019.
10 M. Calderón-Oliver and L. H. López-Hernández, Food Vegetable and Fruit Waste Used in Meat Products, *Food Reviews Int.*, 2020, **38**(6), 628–654, DOI: 10.1080/87559129.2020.1740732.
11 A. Zahid and R. Khedkar, Valorisation of Fruit & Vegetable Wastes: A Review, *Current Nutri. Food Sci.*, 2021, **17**(5), 519–528, DOI: 10.2174/1573401317666210913095237.
12 N. Mirabella, V. Castellani and S. Sala, Current options for the valorization of food manufacturing waste: a review, *J. Cleaner Prod.*, 2014, **65**, 28–41, DOI: 10.1016/j.jclepro.2013.10.051.
13 P. F. Perez, R. J. Jagus, M. V. Agüero and M. V. Fernandez, Valorization of Horticultural by-Products: Development of a Novel Fresh-Cut Product with Combined Natural Antimicrobials, *Waste Biomass Valoriz.*, 2025, **16**(7), 3647–3658, DOI: 10.1007/s12649-025-02892-2.
14 A. Sarker, R. Ahmmed, S. M. A. Ahsan, J. Rana, M. Ghosh and R. Nandi, A comprehensive review of food waste valorization for the sustainable management of global food waste, *Sustain. Food Technol.*, 2023, **2**(4), 1146–1167, DOI: 10.1039/d3fb00156c.
15 F. S. El-Safy, H. M. A. Soliman and E. A. Mostafa, Utilization of Prickly Pear Peels Flour as a Natural Source of Minerals, Dietary Fiber and Antioxidants: Effect on Cakes Production, *Agronomy*, 2023, **13**(2), 439, DOI: 10.3390/agronomy13020439.
16 S. Surbhi, R. C. Verma, R. Deepak, H. K. Jain and K. K. Yadav, A review: food, chemical composition and utilization of carrot (*Daucus carota* L.) pomace, *Int. J. Chem. Stud.*, 2018, **6**(3), 2921–2926.
17 T. S. Shinali, Y. Zhang, M. Altaf, A. Nsabiyeze, Z. Han, S. Shi and N. Shang, The Valorization of Wastes and Byproducts from Cruciferous Vegetables: A Review on the Potential Utilization of Cabbage, Cauliflower, and Broccoli Byproducts, *Foods*, 2024, **13**(8), 1163, DOI: 10.3390/foods13081163.
18 W. Chihoub, M. I. Dias, L. Barros, R. C. Calhelha, M. J. Alves, F. Harzallah-Skhiri and I. C. F. R. Ferreira, Valorisation of the green waste parts from turnip, radish and wild cardoon: nutritional value, phenolic profile and bioactivity evaluation, *Food Res. Int.*, 2019, **126**, 108651, DOI: 10.1016/j.foodres.2019.108651.

19 A. Zayed and M. A. Farag, Valorization, extraction optimization and technology advancements of artichoke biowastes: food and non-food applications, *LWT–Food Science and Technology*, 2020, **132**, 109883, DOI: 10.1016/j.lwt.2020.109883.
20 D. Caro, Carbon footprint, *Encyclopedia of Ecology*, ed. S. Elias, Elsevier, 2018, pp. 252–257, ISBN: 978-12-409548-9.
21 O. Panza, A. Conte and M. A. Del Nobile, Pomegranate By-Products as Natural Preservative to Prolong the Shelf Life of Breaded Cod Stick, *Molecules*, 2021, **26**(8), 2385, DOI: 10.3390/molecules26082385.
22 A. Cedola, A. Cardinali, M. A. Del Nobile and A. Conte, Enrichment of bread with olive oil industrial by-product, *J. Agric. Sci. Technol.*, 2019, **9**(2), 119–127, DOI: 10.17265/2161-6262/2019.02.006.
23 V. Marinelli, A. Lucera, A. L. Incoronato, L. Morcavallo, M. A. Del Nobile and A. Conte, Strategies for fortified sustainable food: the case of watermelon-based candy, *J. Food Sci. Technol.*, 2021, **8**(3), 894–901, DOI: 10.1007/s13197-020-04595-5.
24 AOAC 985.29-1986, *Total Dietary Fiber in Foods. Enzymatic-Gravimetric Method*, AOAC International, Rockville, MA, USA, 2003.
25 R. L. Doty, P. Shaman, S. L. Applebaum, R. Giberson, L. Siksorski and L. Rosenberg, Smell identification ability: changes with age, *Science*, 1984, **226**(4681), 1441–1443, DOI: 10.1126/science.6505700.
26 J. B. Guinée, *Handbook on life cycle assessment: operational guide to the ISO standards*, Springer Science & Business Media, 2002, vol. 7.
27 ISO, *207 (2006) ISO 14040: 2006 Environmental Management—Life Cycle Assessment—Principles and Framework*, ISO, Switzerland, 2006.
28 B. P. W. H. Weidema, H. Wenzel, C. Petersen and K. Hansen, The product, functional unit and reference flows in LCA, *Environ. News*, 2004, **70**, 1–46.
29 S. A. Siddiqui, I. Khalifa, T. Yin, M. K. Morsy, R. M. Khoder, M. Salauddin and N. Khalid, Valorization of plant proteins for meat analogues design—a comprehensive review, *Eur. Food Res. Technol.*, 2024, **250**(10), 2479–2513, DOI: 10.1007/s00217-024-04565-1.
30 R. N. Ratu, I. D. Veleşcu, F. Stoica, A. Usturoi, V. Arseboaia, I. C. Crivei and I. S. Brumă, Application of agri-food by-products in the food industry, *Agriculture*, 2023, **13**(8), 1559, DOI: 10.3390/agriculture13081559.
31 M. Gómez and M. M. Martinez, Fruit and vegetable by-products as novel ingredients to improve the nutritional quality of baked goods, *Crit. Rev. Food Sci. Nutr.*, 2018, **58**(13), 2119–2135, DOI: 10.1080/10408398.2017.1305946.
32 B. Socas-Rodríguez, G. Álvarez-Rivera, A. Valdés, E. Ibáñez and A. Cifuentes, Food by-products and food wastes: are they safe enough for their valorization?, *Trends Food Sci. Technol.*, 2021, **114**, 133–147.
33 I. Buljeta, D. Šubarić, J. Babić, A. Pichler, J. Šimunovic and M. Kopjar, Extraction of dietary fibers from plant-based industry waste: a comprehensive review, *Appl. Sci.*, 2023, **13**(16), 9309, DOI: 10.3390/app13169309.
34 D. J. McClements, J. Weiss, A. J. Kinchla, A. A. Nolden and L. Grossmann, Methods for testing the quality attributes of plant-based foods: meat-and processed-meat analogs, *Foods*, 2021, **10**(2), 260, DOI: 10.3390/foods10020260.
35 D. A. Teigiserova, L. Hamelin and T. M. Homsen, Review of high-value food waste and food residues biorefineries with focus on unavoidable wastes from processing, *Resour., Conserv. Recycl.*, 2019, **149**, 413–426, DOI: 10.1016/j.resconrec.2019.05.003.
36 L. Giraldo-Silva, B. Ferreira, E. Rosa and A. C. Dias, Opuntia ficus-indica fruit: a systematic review of its phytochemicals and pharmacological activities, *Plants*, 2023, **12**(3), 543.
37 T. S. Shinali, M. Zhang, A. Altaf, Z. Nsabiyeze, S. Han, Y. Shi and N. Shang, The valorization of wastes and byproducts from cruciferous vegetables: a review on the potential utilization of cabbage, cauliflower, and broccoli byproducts, *Foods*, 2024, **13**(8), 1163, DOI: 10.3390/foods13081163.
38 P. Ayuso, J. Quizhpe, M. D. L. Á. Rosell, R. Peñalver and G. Nieto, Bioactive compounds, health benefits and food applications of artichoke (Cynara scolymus L.) and artichoke by-products: a review, *Appl. Sci.*, 2024, **14**(11), 4940, DOI: 10.3390/app14114940.
39 R. L. Prior, X. Wu and K. Schaich, Standardized methods for the determination of antioxidant capacity and phenolics in foods and dietary supplements, *J. Agric. Food Chem.*, 2005, **53**(10), 4290–4302, DOI: 10.1021/jf0352520.
40 A. Floegel, D. O. Kim, S. J. Chung, S. I. Koo and O. K. Chun, Comparison of ABTS/DPPH assays to measure antioxidant capacity in popular antioxidant-rich beverages, *J. Func. Foods*, 2011, **3**(2), 103–111, DOI: 10.1016/j.jff.2011.01.005.
41 D. Huang, B. Ou and R. L. Prior, The chemistry behind antioxidant capacity assays, *J. Agricul. Food Chem.*, 2005, **53**(6), 1841–1856, DOI: 10.1021/jf030723c.
42 V. L. Singleton, R. Orthofer and R. M. Lamuela-Raventos, Analysis of total phenols and other oxidation substrates and antioxidants by means of Folin-Ciocalteu reagent, *Methods Enzymol.*, 1999, **299**, 152–178, DOI: 10.1016/S0076-6879(99)99017-1.
43 A. Moure, J. M. Cruz, D. Franco, J. M. Domínguez, J. Sineiro and J. C. Parajó, Antiradical activity of extracts from onion and broccoli industrial by-products, *Food Chem.*, 2001, **75**(4), 437–444, DOI: 10.1016/S0308-8146(01)00216-3.
44 A. Zayed and M. A. Farag, Valorization, extraction optimization and technology advancements of artichoke biowastes: food and non-food applications, *LWT–Food Science and Technology*, 2020, **132**, 109883, DOI: 10.1016/j.lwt.2020.109883.
45 D. J. McClements, *Food Emulsions: Principles, Practices, and Techniques*, CRC Press, Boca Raton, FL, USA, 2016.
46 M. Bolger and J. McCarthy, Food Systems, Food Environments, and Consumer Behavior, in *Sustainable Food Systems and Food Environments*, ed. J. Fanzo and C. Davis, Springer, Cham, 2018, pp. 3–19.
47 M. Friedman, Food browning and its prevention: an overview, *J. Agric. Food Chem.*, 1996, **44**(3), 631–653, DOI: 10.1021/jf950334c.

48 M. C. Nicoli, M. Anese and M. Parpinel, Influence of processing on the antioxidant properties of fruit and vegetables, *Trends in Food Sci. Technol.*, 1999, **10**(3), 94–100.
49 F. Shahidi and Y. Pan, Influence of food matrix and food processing on the chemical interaction and bioaccessibility of dietary phytochemicals: a review, *Crit. Rev. Food Sci. Nutr.*, 2022, **62**(23), 6421–6445, DOI: 10.1080/10408398.2021.1901650.
50 M. Palermo, N. Pellegrini and V. Fogliano, The effect of cooking on the phytochemical content of vegetables, *J. Sci. Food Agric.*, 2014, **94**(6), 1057–1070, DOI: 10.1002/jsfa.6478.
51 M. I. Luca, M. Ungureanu-Iuga and S. Mironeasa, Carrot pomace characterization for application in cereal-based products, *Appl. Sci.*, 2022, **12**(16), 7989, DOI: 10.3390/app12167989.
52 K. Q. Lau, M. R. Sabran and S. R. Shafie, Utilization of vegetable and fruit by-products as functional ingredient and food, *Front. Nutr.*, 2021, **8**, 661693, DOI: 10.3389/fnut.2021.661693.
53 N. Jiménez-Moreno, I. Esparza, F. Bimbela, L. M. Gandía and C. Ancín-Azpilicueta, Valorization of selected fruit and vegetable wastes as bioactive compounds: opportunities and challenges, *Crit. Rev. Environ. Sci. Technol.*, 2020, **50**(20), 2061–2108, DOI: 10.1080/10643389.2019.1694819.
54 A. C. Orădan, A. V. Timar, A. R. Memete, C. A. Rosan, A. C. Teusdea and S. I. Vicaș, The effects of different concentrations of Prunus serotina extract on the quality characteristics of raw and cooked pork burger, *Bull. UASVM Food Sci. Technol.*, 2024, **81**, 114–132.
55 R. Oliver-Simancas, L. Labrador-Fernández, C. Abellán-Diéguez, A. García-Villegas, A. Del Caro, F. J. Leyva-Jimenez and M. E. Alañón, Valorization applications of pineapple and papaya byproducts in food industry, *Compr. Rev. Food Sci. Food Saf.*, 2024, **23**(3), e13359.
56 I. Zahari, K. Östbring, J. K. Purhagen and M. Rayner, Plant-based meat analogues from alternative protein: a systematic literature review, *Foods*, 2022, **11**(18), 2870, DOI: 10.3390/foods11182870.
57 K. Younis, A. Ashfaq, A. Ahmad, Z. Anjum and O. Yousuf, A critical review focusing the effect of ingredients on the textural properties of plant-based meat products, *J. Texture Stud.*, 2023, **54**(3), 365–382, DOI: 10.1111/jtxs.12704.
58 B. Nabil, R. Ouaabou, M. Ouhammou, L. Essaadouni and M. Mahrouz, Functional properties, antioxidant activity, and organoleptic quality of novel biscuit produced by moroccan cladode flour "*Opuntia ficus-indica*, *J. Food Qual.*, 2020, (1), 3542398, DOI: 10.1155/2020/3542398.
59 K. D. Sharma, S. Karki, N. S. Thakur and S. Attri, Chemical composition, functional properties and processing of carrot—a review, *J. Food Sci. Technol.*, 2012, **49**(1), 22–32, DOI: 10.1007/s13197-011-0310-7.
60 R. P. Turcu, T. D. Panaite, A. E. Untea, C. □oica, M. Iuga and S. Mironeasa, Effects of supplementing grape pomace to broilers fed polyunsaturated fatty acids enriched diets on meat quality, *Animals*, 2020, **10**(6), 947.
61 A. E. Bilek and S. Turhan, Enhancement of the nutritional status of beef patties by adding flaxseed flour, *Meat Sci.*, 2009, **82**(4), 472–477.
62 A. Le Rose, O. Panza, D. Caro, A. Conte and M. A. Del Nobile, Cheesecake Customized Using Juice and By-Products from Prickly Pears: A Case Study of Recycling and Environmental Impact Evaluation, *Foods*, 2025, **14**(7), 1159, DOI: 10.3390/foods14071159.
63 M. Bruno, M. Thomsen, F. M. Pulselli, N. Patrizi, M. Marini and D. Caro, The carbon footprint of Danish diets, *Clim. Change*, 2019, **156**(4), 489–507, DOI: 10.1007/s10584-019-02508-4.
64 M. Karwacka, A. Ciurzyńska, A. Lenart and M. Janowicz, Sustainable development in the agri-food sector in terms of the carbon footprint: a review, *Sustainability*, 2020, **12**(16), 6463, DOI: 10.3390/su12166463.
65 D. Caro, P. Frederiksen, M. Thomsen and A. B. Pedersen, Toward a more consistent combined approach of reduction targets and climate policy regulations: the illustrative case of a meat tax in Denmark, *Environ. Sci. Policy*, 2017, **76**, 78–81.
66 S. Säll and M. Gren, Effects of an environmental tax on meat and dairy consumption in Sweden, *Food Policy*, 2015, **55**, 41–53.
67 I. M. Gren, E. Moberg and E. Röös, Design of a climate tax on food consumption: examples of tomatoes and beef in Sweden, *J. Cleaner Prod.*, 2019, **211**, 1576–1585.
68 A. Lordi, D. Caro, A. Le Rose, M. A. Del Nobile and A. Conte, Quality and environmental impact of meat burgers fortified with tomato by-products, *LWT–Food Science and Technology*, 2025, 118182, DOI: 10.1016/j.lwt.2025.118182.

