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Hazelnut skin polyphenolic green extract as a promising natural antioxidant in pork burgers: Assessment of quality parameters and consumer acceptance☆

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ABSTRACT

Given the increasing consumer focus on healthier and environmentally friendly foods, the use of natural antioxidants in food production is becoming more common. The recovery of these antioxidants from agri-food waste is crucial for a circular economy, as it revalues matrices that would otherwise become waste. This study aimed to assess the antioxidant capacity of hazelnut skin and its green polyphenolic extract and to evaluate their effect on some qualitative parameters of pork burgers. Three types of burgers were formulated: a control group, and two experimental groups with the addition of 2.5 % of hazelnut skin or 1 % of hazelnut green extract. On days 0 and 7 of refrigerated storage (0–2 °C) parameters such as color, cooking losses, tenderness, lipid oxidation, and volatile profile were evaluated. Additionally, a group of panelists was asked to assess the acceptability of color and the potential for purchase. In both raw and cooked burgers, at all times examined, the two experimental groups showed a significant improvement in oxidative stability and lower production of volatile fat oxidation compounds compared to the control in which the main indicators of pork meat spoilage were detected. Although, even if on the 7th day of storage, the HS and HSE burgers exhibited better color stability, these groups showed a worsening in terms of color acceptability and tenderness. Overall, despite trade-offs, the hazelnut skin and their green extract showed high potential to emerge as food additives in meat products.

1. Introduction

Lipid oxidation represents one of the main chemical processes that affect the quality and shelf-life of meat and meat products. This phenomenon involves the degradation of unsaturated fatty acids present in lipids, leading to the formation of secondary compounds such as aldehydes and ketones, which are responsible for sensory and nutritional alterations (Wang et al., 2023). In addition to compromising the taste, aroma, and color of the meat, lipid oxidation is associated with a reduction in food safety, as it can promote the formation of potentially harmful compounds such as hexanal, pentanal, heptanal and octanal that are responsible for quality deterioration and represent health risks, including carcinogenesis (Arabshahi-Delouee et al., 2007). Generally, synthetic antioxidants are used to prevent this phenomenon but in recent years, the discussion around the use of synthetic antioxidants in animal production has intensified, driven by growing health concerns and the demand for more natural food products. The most commonly used synthetic antioxidants in food are phenolic antioxidants (Rodil et al., 2012), for example, butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), and tertiary butylhydroquinone (TBHQ). The toxicity of BHA, BHT, and TBHQ has been investigated extensively using a variety of experimental conditions and the results show that an excessive addition or incorrect use of synthetic phenolic antioxidants results in carcinogenicity, cytotoxicity, oxidative stress induction, endocrine disrupting effects, which warrant attention (Xu et al., 2021).

This problem and the shift in consumer preferences have catalyzed a

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surge in research focused on developing and applying natural antioxidants in food production systems (López-Pedrouso et al., 2022; Novais et al., 2022; Pateiro et al., 2021). Notably, several studies reported that various plant extracts, that support consumer health, might even have an antioxidant capacity stronger than synthetic antioxidants (Jayawardana et al., 2019; Zhang et al., 2018). In particular, polyphenol extracts, renowned for their antioxidant properties, are increasingly being studied for their application in meat products (Gutiérrez-del-Río et al., 2021; Manessis et al., 2020; Munekata et al., 2020). It is well known that agro-industrial wastes are a great source of phenolic compounds with antioxidant power.

Agro-industries generate numerous waste materials rich in bioactive compounds very interesting from a technological and nutritional point of view. The recovery of these bioactive compounds from agricultural and food industry waste presents a unique opportunity to enhance the sustainability of food production. Utilizing these compounds not only contributes to the creation of healthier animal products but also supports the principles of a circular economy by revaluing waste materials that would otherwise contribute to environmental degradation aligning seamlessly with the goals of the Green New Deal.

However, it is noteworthy that most natural extracts are currently obtained using solvent-based methods (Bubalo et al., 2018), which may pose sustainability and food safety challenges. Since most bioactive compounds are not soluble in water, conventional extraction methods are very time-consuming, labor-intensive, and require large amounts of solvents like alcohols, hydrocarbons, and chloroalkanes. In the end, these methods may result in some target molecule degradation and partial volatile loss (Cravotto et al., 2008).

Above all, the yield is frequently extremely low despite the considerable energy consumption and the vast number of solvents (Chemat et al., 2012).

To address these challenges, it is necessary to develop and implement green extraction techniques such as supercritical fluid extraction, microwave-assisted extraction, and ultrasound-assisted extraction, that use less harmful solvents or none at all, reducing the environmental footprint and improving the safety profile of the extracts (Carpentieri et al., 2021).

An innovative example that combines a valuable by-product and a green extraction technique is the phenolic extract from hazelnut skin. Italy is the second-largest producer of hazelnuts, accounting for nearly 20 percent of global production and 15 percent of exports. It also has the highest per capita annual hazelnut consumption among producing countries, at 0.520 kg per person. It is estimated that 90 % of the hazelnuts produced in Italy go to processors while the remaining 10 % are destined for fresh consumption (Forte et al., 2022; Misachi, 2018), this means that just under 3 k tons of hazelnut skin are made in Italy yearly from an average annual hazelnut production of about 110 k tons (FAOSTAT, 2023). The well-documented properties of hazelnut skin, particularly its high polyphenol content, have spurred interest in its application within the food industry (Ollani et al., 2024). Various studies have already explored the potential uses of hazelnut skin (Bertolino et al., 2015; Costantini et al., 2023) and demonstrated its effectiveness as a natural preservative in meat (D'Ambra et al., 2023). Its potential is continuously being studied, particularly Capaldi et al. (2025), who investigated the development of a green phenolic extract through subcritical water extraction of bioactive compounds. The evaluation of polyphenolic profiles and antioxidant activities of this extract provided promising results compared to the benchmark of reflux maceration, both in the laboratory and on a semi-industrial scale.

This study aims to characterize the antioxidant power of hazelnut skin and a green phenolic extract obtained from hazelnut skin and to explore and validate their effects on the oxidative stability and chemical and sensory properties of pork burgers during refrigerated storage.

2. Material and methods

2.1. Hazelnut skin (HS) and hazelnut skin extract (HSE)

The selection of HS as by-product for this study is rooted in its dual potential as a functional ingredient and a sustainable raw material. Our previous study confirmed the potential of hazelnut skin as an effective antioxidant and nutritional additive (D'Ambra et al., 2023). Building on these findings, the current study utilizes it as a positive control and further investigates its functionality to validate and expand upon its beneficial properties. Different Italian companies supplied HS that had the following nutritional composition: moisture 5.3 %, lipid 24.4 %, protein 6 %, fiber 21.7 %, and saturated fatty acids 9.2 %, monounsaturated fatty acids 77.2 %, polyunsaturated fatty acids 13.6 % as % of total fatty acids. Instead, the HSE was produced by the University of Turin as described by Capaldi et al. (2025) from the same hazelnut skin.

2.2. Extraction of phenolic compounds and antioxidant activity

The HS required the free phenolic extraction process to undergo assays to characterize the total phenolic content and antioxidant activity while HSE was directly diluted in water and used for the assays. The extraction of free phenolic compounds from the HS was performed according to the method described by D'Ambra et al. (2023) with some modifications. Briefly, 2.5 g of this by-product was homogenized with 12.5 mL of a methanol/water/formic acid solution (in the ratio 70:28:2, v/v/v) using an Ultra-Turrax homogenizer (IKA, Germany) for 1 min. The resulting suspension was centrifuged at 6000 rpm for 15 min at 4 °C, using a Remi Elektrotechnik LTD (Model NEYA 16R, Mumbai, India). The supernatant was accumulated, and the pellet was resuspended with 12.5 mL of fresh solution. This process was repeated thrice to fully extract the phenolic compounds from the initial 2.5 g sample. The polyphenol-rich extracts obtained were stored at 0–4 °C for subsequent analyses.

2.2.1. Total phenolic content (TPC)

The total phenolic content of HS and HSE was determined using the Folin-Ciocalteu assay (Singleton et al., 1999) with some modifications: 1975 μL of distilled water was mixed with 25 μL of the sample and 125 μL of Folin reagent (1.8–2.2 mol/L). After exactly one minute, 375 μL of 20 % Na_2CO_3 was added, and the samples were stored in the dark for 2 h. At the end of incubation, absorbance values were measured at 765 nm using a Jasco spectrophotometer (Model V550, UV/VIS, Tokyo, Japan). The standard used to create the calibration curve was gallic acid, so the results are expressed as milligrams of gallic acid equivalent/grams by-products (mg GAE/g).

2.2.2. ABTS assay

The antioxidant activity of HS and HSE was evaluated as described by Re et al. (1999) with the ABTS method. This assay uses the chromogen 2,2′-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS, AppliChem GmbH). The antioxidant capacity is measured by the reduction in absorbance at 734 nm of the ABTS•+ radical cation in the presence of antioxidants. The ABTS radical cation (ABTS•+) is produced by combining a 7 mM aqueous solution of ABTS with 2.45 mM potassium persulfate and allowing the mixture to react in the dark overnight. The ABTS•+ solution is then diluted in methanol to achieve an absorbance (A_0) of 0.705 ± 0.005 at 734 nm. Next, 100 μL of the diluted

sample was combined with 1400 μL of ABTS•+ solution and kept at 20°C for 10 min in the dark. The final absorbance at 734 nm (A_f) was measured. The percentage of scavenging (*S%*) was calculated using the ensuing formula:

$$S\% = \left((A_0 - A_f)/A_0\right)x100$$

A_0 represents the initial absorbance (control), and A_f represents the final absorbance (sample). The standard for constructing the calibration curve is Trolox (6-hydroxy-2,5,6,7-tetramethylchroman-2-carboxylic acid), therefore, the antioxidant activity was expressed as mmol of Trolox equivalent per gram of by-product.

2.2.3. FRAP assay

The antioxidant capacity of HS and HSE was also measured as ferric reducing/antioxidant power by adopting FRAP assay as described by Benzie and Strain (1999). The procedure is grounded on reducing the Fe^{3+}–2,4,6-tripyridyl-s-triazine (TPTZ) complex to its ferrous form under acidic conditions. Concisely, 3 mL of the FRAP assay solution (composed of 20 mM ferric chloride solution, 10 mM TPTZ solution, and 0.3 M acetate buffer at pH 3.6) was prepared daily and united with 100 μL of the sample. The absorbance was recorded at 593 nm at ambient temperature after 6 min of incubation. The results were reported as μmol of $FeSO_4$ per gram of by-product.

2.2.4. DPPH assay

The DPPH method for estimating the antioxidant activity of HS and HSE was performed according to the method described by Helal et al. (2012). A DPPH (2,2-diphenyl-1-picrylhydrazy) solution (0.1 mM) was prepared in methanol and kept in darkness for 30 min to complete the reaction. After that 200 μL of the samples were mixed with 2 mL of DPPH solution and incubated in the dark in a shaker for 30 min. Then the absorbance of the resulting solutions was measured at 517 nm using a UV–visible spectrophotometer against a blank without a sample. The activity was calculated after the sample blank subtraction and expressed as mg of vitamin C per gram of sample.

2.2.5. Identification and quantification of phenolic compounds in hazelnut skin and hazelnut skin green extract by high-resolution mass spectrometry (UHPLC/MS)

The phenolic compound profiles of HS and HSE were determined as reported in Cattivelli et al. (2023). Before the injection in the high-resolution mass spectrometer, phenolic compounds were extracted from the samples by following the protocol previously described in Section 2.2. of this paper. Phenolic compounds were firstly separated using a C18 column (Acquity UPLC HSS C18 Reversed phase, 2.1 × 100 mm, 1.8 μm particle size, Waters, Milan, Italy) in an UHPLC Ultimate 3000 module (Thermo Fisher Scientific, San Jose, CA, USA) before being analyzed with a Q Exactive Hybrid Quadrupole-Orbitrap Mass Spectrometer (Thermo Fisher Scientific, San Jose, CA, USA). The chromatographic separation and mass spectrometry settings are fully described in Martini et al. (2020). Quantification was carried out by building external calibration curves with the available standard compounds, as reported in Table S1 of Supplementary Material.

2.3. Pork burgers formulation

Burgers were prepared by grinding pork loin, with an average value of pH of 5.71 ± 0.06, with backfat purchased from the commercial market using an electrical grinder with a sieve of 7 mm of diameter (Trita Express, R.G.V. s.r.l., Como, Italy). Three types of burgers were formulated: a control burger with 88.5 % *Longissimus dorsi* muscle, 10 % subcutaneous adipose tissue, and 1.5 % sodium chloride; and two other groups with the addition of 2.5 % hazelnut skin (HS) and 1 % phenolic extract (HSE), respectively. The burgers were modeled using a burger press (50 g ± 0.5 g minced meat, 6 cm in diameter and 1 cm in thickness). The concentrations were chosen based on the study conducted by D'Ambra et al. (2023) and taking into account the total polyphenol content and the antioxidant activity shown *in vitro* by the products. The analyses were conducted three times in triplicate. For each cycle, 9 burgers (3 of each type) were analyzed at day 0 (T_0), and 9 burgers were stored in a refrigerator at a temperature of 4 °C in a resealable polypropylene package with a capacity of 750 cc, normally used for domestic food storage (Contital s.r.l), in an unmodified atmosphere, for the analysis at day 7 (T_7). The cooking was done using a double plate grill (Bosch, Germany) at 180 °C for 3 min (core temperature reached 88.7 ± 4.5 °C).

2.4. Pork burger analysis

On each sampling day, the samples were subjected to various analyses, including the determination and evaluation of color, cooking loss, oxidation status (TBARS), volatile profile (HS-SPME), tenderness, fatty acid profile, and visual sensory acceptability analysis.

2.4.1. Color

Color of burgers was assessed on raw samples at T_0 and T_7 using a Minolta CM-600d spectrophotometer (Konica Minolta Holdings, Inc, Osaka, Japan) with a window diameter of 8 mm, D65 as the light source, and 10° observer value. The colorimeter was calibrated with a standard white plate before each measurement session. Three readings were taken at different side points of burgers per treatment and the measurement was made by pointing the colorimeter perpendicularly to the surface of the burgers. The values obtained from three measurements for each sample were collected, and the average was recorded. Color determination was executed according to the CIE L*a*b* color convention (CIE, 1986), in which there are three basic coordinates: L^* – "lightness"; a^* – "redness"; b^* – "yellowness". The results were expressed as

$$\Delta E = \sqrt{(L^*_0 - L^*_7)^2 + (a^*_0 - a^*_7)^2 + (b^*_0 - b^*_7)^2}$$

2.4.2. Cooking loss

For the determination of cooking loss, burgers were weighed before and after cooking on a home electric double-cast grill plate (Bosch, Germany) at 180 °C for 3 min. The parameter was determined in triplicate. Cooking loss percentages were then calculated as follows and as reported in a previous paper (D'Ambra et al., 2023):

$$Cooking\ \ loss(\%) = \frac{weight\ \ raw - weight\ \ cooked}{weight\ \ raw}x100$$

2.4.3. Determination of oxidative stability

Lipid oxidation of raw and cooked burgers was determined by the thiobarbituric acid reactive substances (TBARS) assay using the method by Siu and Draper (1978). Initially, 2.5 g of minced burger were placed in an ice bath and homogenized with 12.5 mL of distilled water at 9500 rpm for 2 min utilizing an Ultra-Turrax homogenizer (IKA, Germany). Then, 12.5 mL of trichloroacetic acid (TCA) 10 % (Sigma-Aldrich, Milan, Italy) was added and the sample was centrifugated at 2000 rpm for 20

min at 4 °C. The supernatant was taken and filtered across Whatman No. 5 filter paper and 4 mL of this filtrate was relocated into Pyrex test tubes. A blank sample was prepared simultaneously (2 mL of distilled water + 2 mL of TCA solution + 1 mL of TBA). After that, 1 mL of 2-thiobarbituric acid (TBA, Sigma-Aldrich, Milan, Italy) 0.06 M was added in each tube and all samples were incubated in a water bath at 80 °C for 90 min. After cooling, the absorbance at 532 nm was measured using a Jasco spectrophotometer (Model V550, UV/VIS, Tokyo, Japan). TBARS were expressed as mg of malondialdehyde (MDA) per kg of burger, using 1,1,3,3-tetraethoxypropane (TEP, Sigma-Aldrich, Milan, Italy) as a standard. Moreover, the antioxidant power was calculated as the following equation and expressed as a percentage of antioxidant activity (*AOA*) (Wijewickreme & Kitts, 1998):

$$\%\ AOA = \frac{[TBARS\ value\ of\ the\ control - TBARS\ of\ the\ test\ sample]}{[TBARS\ value\ of\ the\ control]} x100$$

2.4.4. Determination of volatiles profile

Volatile profile was determined by headspace solid phase microextraction (HS-SPME) followed by gas chromatography/mass spectrometry (GC/MS) as described by Lopez-Moreno et al. (2023) with some modifications. The determination was performed on C, HS, and HSE samples, to evaluate the influence of both treatments on the formation of volatile lipid oxidation compounds during storage and cooking. The analysis was performed after 0 and 7 days of refrigerated storage. Four grams of raw burgers were weighted into 25-mL screw-cap glass vials provided with Mininert® valves (Merck KGaA, Darmstadt, Germany). Samples were conditioned at 80 °C for 30 min using a thermoblock (Falc Instruments, Treviglio, Italy). Subsequently, a triphasic SPME fibre DVB/CAR/PDMS (divinylbenzene/carboxen/polydimethylsiloxane) was exposed in the headspace for 30 min at 80 °C to extract the volatile compounds. The analysis was carried out using an Agilent 6890 Gas Chromatograph coupled to a mass spectrometer Agilent 5973 N Mass Selective Detector (MSD) (Agilent Technologies Inc., Santa Clara, CA, USA). Desorption of analytes from the fibre was performed in splitless mode at 240 °C for 5 min into the GC injector port. Helium was used as carrier gas for the chromatographic separation at a flow rate of 1 mL/min and the detector temperature was set at 240 °C. The column was maintained at 40 °C for 5 min, incrementally warmed to 150 °C at a rate of 5 °C/min, and ultimately elevated to 240 °C at 8 °C/min, where it was sustained for an additional 5 min. The mass spectrometer was recorded in positive mode $m/z = 30–180$ in full scan. Peak identification was carried out by comparison with system libraries (Wiley, NIST). Compounds were correctly identified if the library match factor was 50 % or more. The circumstance that the same compound appeared in at least 50 % of the samples was also considered. The abundance of aromatic compounds was determined by normalising the area of a compound to the total peak area of the chromatogram. The analyses were performed in duplicate.

2.4.5. Instrumental tenderness

To evaluate the tenderness of burgers by Warner-Bratzler shear force (WBSF) measurements reported by Belmonte et al. (2021) 3 cylindrical subsamples of approximately 10 mm in diameter were excised in triplicate from each type of cooked burger. The height of each sample was measured with a caliper. The analysis used a dynamometer (Z1.0, ZwickRoll, Ulm, Germany) with a 1kN load cell. The test involved uniaxial compression with a flat cylinder. The specific settings were: distance between tools of 50 mm; maximum deformation of 50 %; test speed of 10 mm/min; and preload dynamometer of 1 N. The data were processed using the software TestXpert® II 161 (v3.31, ZwickRoll GmbH & Co. KG, Ulm, Germany). The results were expressed as the maximum force (N) required to reach 50 % deformation.

2.4.6. Fatty acid profile

Following the method, lipids from raw pork burgers were extracted using a chloroform–methanol mixture (Folch et al., 1957), and the fatty acid composition was analyzed through capillary gas chromatography. According to Zappaterra et al. (2020), 50 mg of lipid extract was mixed with 2 mL of hexane and subjected to methylation using 200 μL of a 2 N potassium hydroxide methanolic solution (KOH provided by Carlo Erba, Milan, Italy, and methanol provided by ITW Reagents, Barcelona, Spain).

Consequently, the fatty acid methyl esters (FAMEs) were analyzed using a TRACE™GC Ultra gas chromatograph (Thermo Electron Corporation, Rodano, Milan, Italy) equipped with a Flame Ionization Detector, a Programmable Temperature Vaporizing (PVT) injector, and a TR-FAME Column (30 m long, 0.25 mm i.d., 0.2 μm film thickness) furnished by Thermo Fisher Scientific (Rodano, Milan, Italy). One μL of the methylated esters sample was injected into the gas chromatograph with a split flow rate of 10 mL/min, working at an uninterrupted helium flow of 1 mL/min as the carrier gas. The injector and detector temperatures were set at 240 °C. The temperature program began at 140 °C and increased by 4 °C/min to 250 °C, where it was retained for 5 min. The Chrom-card software (version 2.3.3, Thermo Electron Corporation, Rodano, Milan, Italy) was used to designate, identify, and integrate the peaks area. A solution of known concentrations of a standard fatty acid mix (Supelco 37 Component FAME mix, PUFA standard n.2, Animal Source, Supelco, Bellefonte, PA, USA, and single FAMEs standard, Larodan, Fine Chemicals AB, Malmö, Sweden) was used to distinguish the retention times of the FAMEs. The measure of each FAME was expressed as the relative percentage of the total amount of FAMEs using the normalized and correct area method.

2.4.7. Sensory analysis

The sensory analysis was conducted exclusively on raw burgers to evaluate acceptability of color and purchase intent (Lawless & Heymann, 2010). Panels of 15 judges from the Department of Life Science staff were selected for sensory analysis. The panel was regularly split by gender, with ages ranging from 20 to 40 years. All participants had prior experience with sensory analysis and had been specifically trained for this type of test. The panel was conducted in a teaching laboratory with natural lighting, and each judge was seated at least one and a half meters apart. An affective test with a hedonic scale (from 0 to 5) was used; it was required to express an opinion on 2 parameters: color (0 = not acceptable; 5 = acceptable) and willingness to purchase (yes or not), and any notes or comments on the product. The results are expressed as the average of 45 sensory tests conducted at both sampling times across the three trials of the experiment.

2.5. Statistical analysis

Data regarding the characterization of by-products (TPC, ABTS, FRAP, DPPH, and phenolic compound profiles) were expressed as mean ± standard deviation (SD) of three samples analyzed in triplicate. Data from burger analyses were submitted to analysis of variance using the GLM procedure of SAS (SAS Institute Inc., Cary, NC, USA), assuming a level of at least $P < 0.05$ for statistical significance. The statistical models included as fixed effects the treatments (C, HS, and HSE), the storage days (0 and 7), and relative interactions. The differences between means were tested by *t*-test (SAS/GLM PDIFF option).

Table 1
Total phenolic content (TPC) and antioxidant activity (ABTS, FRAP, and DPPH) of HS and HSE (Mean ± SD).

	Hazelnut skin	Hazelnut skin green extract
TPC (mg GAE/g)	174.61 ± 17.3	605.21 ± 11.3
ABTS (mmol Trolox eq/g)	1096.29 ± 19.3	2472.73 ± 154.3
FRAP (μmol $FeSO_4$/g)	784.34 ± 10.2	2951.37 ± 13.6
DPPH (mg Vitamin C/g)	272.68 ± 5.9	793.10 ± 32.2

3. Results and discussion

3.1. Total phenolic content and antioxidant activity of by-products

HS had lower levels of total phenolic compounds and FRAP, but its ABTS and DPPH values were comparable to or higher than those reported by other Authors (Bertolino et al., 2015; Del Rio et al., 2011; Kruk et al., 2024; Özdemir et al., 2014). As for HSE, the TPC value was lower compared to that reported by the researchers who produced it, which was close to 800 mg/g GAE eq (Capaldi et al., 2025).

Table 1 reports the phenolic content and antioxidant activity of the by-products.

3.2. Phenolic compound profiles of hazelnut skin and hazelnut skin green extract

As expected, the phenolic profiles of HS and HSE were dominated qualitatively and quantitatively by flavan-3-ols. The quantitative data are reported in Table 2.

The total amount of phenolic compounds was significantly higher in the HSE (1121.08 ± 4.76 mg/100 g) with respect to the HS (425.11 ± 20.23 mg/100 g). The most representative class of phenolic compounds in both samples was flavan-3-ols, which represented 71.3 % and 82.5 % of total phenolic compounds in HS and HSE, respectively. The amount of total flavan-3-ols was significantly higher in HSE with respect to HS. Considering the individual flavan-3-ols, the profile between the two samples was quite different. The compound present in the highest amount in HSE was epicatechin, which accounted for 48.3 % of total flavan-3-ols, followed by catechin (accounting for 26.2 % of total flavan-3-ols) and procyanidin dimer B-type (three isomers accounting for 12.3 % of total flavan-3-ols). Differently, in HS, the most concentrated compound was procyanidin dimer B-type (three isomers accounting for 44.1 % of total flavan-3-ols), followed by epicatechin, which accounted for 27.0 % of total flavan-3-ols.

Table 2
Amount of phenolic compounds identified in HS and HSE. Results are expressed in mg of phenolic compound/100 g of sample.

Compound	Hazelnut skin	Hazelnut skin green extract
Protocatechuic acid	3.05 ± 0.05	7.49 ± 0.28
Gallic acid	2.48 ± 0.07	13.13 ± 0.39
Coumaric acid-*O*-pentoside	5.56 ± 0.06	2.36 ± 0.03
Ellagic acid	0.83 ± 0.11	71.77 ± 5.52
Galloyl shikimic acid (two isomers)	1.64 ± 0.03	6.35 ± 0.17
Galloyl-hexoside (three isomers)	0.22 ± 0.01	1.56 ± 0.02
Syringic acid-4-*O*-hexoside	3.20 ± 0.01	5.85 ± 0.22
Total phenolic acids	***16.98 ± 0.34***	***108.52 ± 0.58***
Epicatechin	81.82 ± 5.46	446.89 ± 11.96
Catechin	22.14 ± 1.06	242.28 ± 7.76
Epigallocatechin	1.39 ± 0.01	19.04 ± 0.41
Gallocatechin	0.40 ± 0.02	9.94 ± 0.35
Catechin-3-*O*-sulphate	n.d.	4.85 ± 0.33
Epicatechin-3-*O*-gallate	4.20 ± 0.13	27.16 ± 0.98
Catechin-3-*O*-hexoside	0.10 ± 0.00	0.24 ± 0.03
Epigallocatechin-3-*O*-gallate	0.15 ± 0.01	0.71 ± 0.02
Gallocatechin-3-*O*-gallate	n.d.	0.97 ± 0.02
Procyanidin dimer A-type (three isomers)	3.60 ± 0.24	3.41 ± 0.31
Procyanidin dimer B-type (three isomers)	133.78 ± 2.76	114.01 ± 2.29
(Epi)catechin-(epi)gallocatechin (2 isomers)	22.15 ± 1.68	15.29 ± 0.56
Procyanidin dimer B-type gallate (2 isomers)	4.54 ± 0.32	5.02 ± 0.35
Procyanidin trimer B-type	23.84 ± 0.76	29.36 ± 0.84
Prodelphinidin trimer B-type	5.11 ± 0.33	5.39 ± 0.17
Total flavan-3-ols	***303.22 ± 12.78***	***924.55 ± 4.67***
Quercetin	50.59 ± 5.08	39.08 ± 1.37
Myricetin	5.09 ± 0.05	7.34 ± 0.12
Kaempferol-3-*O*-rhamnoside	1.31 ± 0.09	1.11 ± 0.03
Phloretin-2′-*O*-glucoside	10.62 ± 0.79	17.78 ± 0.44
Quercetin-3-*O*-rhamnoside	30.63 ± 0.84	17.24 ± 0.43
Myricetin-3-*O*-rhamnoside	5.56 ± 0.22	4.55 ± 0.05
Quercetin-3-*O*-rutinoside	0.53 ± 0.05	0.48 ± 0.03
Isorhamnetin-3-*O*-rutinoside	0.59 ± 0.00	0.43 ± 0.02
Total flavonols	***104.92 ± 7.11***	***88.01 ± 0.72***
Total phenolic compounds	***425.11 ± 20.23***	***1121.08 ± 4.76***

n.d. means that the compound was not detected in the sample.

The second most representative class of phenolic compounds in HSE was phenolic acids, which represented 9.7 % of total phenolic compounds. In this sample, the most representative phenolic acids were ellagic acid (71.77 ± 5.52 mg/100 g) and gallic acid (13.13 ± 0.39 mg/100 g). In contrast, flavonols were found in minor amounts, with quercetin being the most representative (39.08 ± 1.37 mg/100 g). Otherwise, in HS, the second most representative class of phenolic compounds was flavonols, which accounted for 24.7 % of total phenolic compounds. The compound present in the highest amount was quercetin (50.59 ± 5.08 mg/100 g), followed by quercetin-3-O-rhamnoside (30.63 ± 0.84 mg/100 g). Only low amounts of phenolic acids were detected in HS. Previous studies showed that flavan-3-ols (and, in particular, monomeric and dimeric catechins) constitute the most abundant class of phenolic compounds in HS (Capaldi et al., 2025; Del Rio et al., 2011). Concerning the class of flavonols, the most representative compounds were quercetin and quercetin-3-*O*-rhamnoside as already reported by Del Rio et al. (2011). In addition, some phenolic acids, such as gallic acid and protocatechuic acid, have already been identified in HS (Pelvan et al., 2018). Anyway, some phenolic compounds present in high concentrations, such as ellagic acid, were identified in the HS for the first time in this study.

3.3. Oxidative state of pork burgers

3.3.1. Lipid oxidation

During storage and cooking the two experimental groups (HS and HSE) showed a significant ($P < 0.01$) improvement in oxidative stability (Fig. 1).

Fig. 1 reports the effect of treatment on MDA content (mg/kg) of burgers during refrigerated storage and cooking.

Both treatments provided an increasing antioxidant capacity (AOA %) consistently close to 50 %. In fact, during storage, HS presents an AOA% of + 51 % while HSE + 49 %. During cooking, HS presents an AOA% of + 51 % at day 0 and + 59 % at day 7 while HSE + 37 % at day 0 and + 54 % at day 7 (data not shown).

Although there are no legal limits for these types of products regarding MDA content, it is believed, as reported by Trindade et al. (2010) in beef and by Longato et al. (2019) in chicken, that the level of MDA during storage should be kept below 2 mg/kg. In the present study, the MDA value was significantly lower during storage and even after cooking (Fig. 1) in the experimental formulations used, further highlighting the protective effect exerted by the hazelnut skin and its phenolic extract. While the MDA content of the control group was always close to or above the target value of 2 mg/kg (Fig. 1).

The results confirmed the antioxidant ability of HS in pork, as previously observed in our study (D'Ambra et al., 2023) and highlighted that HSE has the same antioxidant power when used by balancing their antioxidant compound content. This result is in line with results obtained with other natural extracts used as antioxidants in meat products. In particular, Jayawardana et al. (2019) reported that TBARS values of uncured pork sausages significantly reduced with the addition of different concentrations of black or green tea extract during 5 days of storage and that the inhibition increased as the concentration used increased.

Šojić et al. (2020), on the other hand, achieved a significant

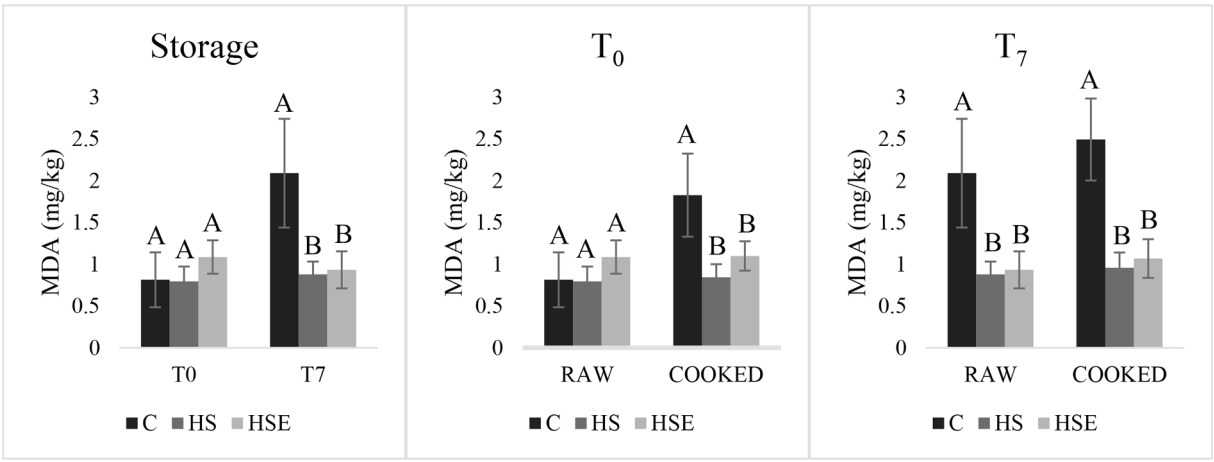

Fig. 1. Effect of treatment on MDA content (mg/kg) of burgers during refrigerated storage and cooking. C: control burgers; HS: hazelnut skin burgers; HSE: hazelnut skin extract burgers. Storage: A, B: different letters indicate statistical differences between groups in each sampling time for $P < 0.01$ T_0 and T_7: A, B: different letters indicate statistical differences between groups within raw and cooked samples for $P < 0.01$.

Table 3
Volatile compounds detected in burgers by SPME analysis. Values are expressed as percentages of the total chromatographic area (%).

RT (min)	Volatile compound	C	HS	HSE
3.129	Pentanal	1.51^{b}	3.10^{a}	2.83^{b}
5.183	Hexanal	22.54^{A}	2.21^{B}	n.d.
8.649	Heptanal	1.69	n.d.	n.d.
9.333	Dodecane	n.d.	1.42	n.d.
9.838	Furan, 2-pentyl-	1.07	1.12	n.d.
10.637	1-Pentanol	1.08	n.d.	n.d.
11.826	Octanal	2.73^{a}	n.d.	0.56^{b}
12.403	Tridecane	n.d.	1.21	n.d.
12.965	2,3-Octanedione	3.09^{A}	0.51^{B}	n.d.
13.617	1-Hexanol	0.51	n.d.	n.d.
14.759	Nonanal	7.99	7.01	6.26
15.171	Tetradecane	n.d.	0.74	0.65
16.042	*trans*-2-octenal	0.94	n.d.	n.d.
16.136	1 Octen 3 ol	7.60^{Aa}	2.40^{Bb}	1.21^{Bc}
16.337	1-heptanol	0.85	1.04	n.d.
17.151	1-Hexanol, 2-ethyl-	n.d.	1.13	0.82
18.658	2-Nonenal, (E)-	0.90	n.d.	n.d.
18.794	Benzaldehyde	2.35	n.d.	n.d.
18.859	1-Octanol	2.98^{A}	3.28^{A}	0.67^{B}
20.214	2-Octen-1-ol, (E)-	1.50^{a}	0.77^{b}	n.d.
21.143	E-2-decenal	1.49	n.d.	n.d.
21.179	Benzeneacetaldehyde	n.d.	3.65	2.10
22.405	Dodecanal	0.37	0.51	0.65
22.801	2,4 nonadienal	0.37	n.d.	n.d.
23.493	3-dodecen-1-al	1.42	n.d.	n.d.
23.954	2,4-Decadienal	0.29	n.d.	n.d.
24.991	trans, *trans*-2,4-Decadienal	0.97	n.d.	n.d.
25.323	E-15-heptadecenal	n.d.	0.58	1.22
27.653	1-Dodecanol	n.d.	3.05	2.55

C: control burgers; HS: hazelnut skin burgers; HSE: hazelnut skin extract burgers.
RT: retention time.
n.d. means that the compound was not detected in the sample.
$^{a, b, c}$: different letters on the same line indicate differences for $P < 0.05$.
$^{A, B, C}$: different letters on the same line indicate differences for $P < 0.01$.

reduction in lipid oxidation using supercritical extracts of wild thyme by-products as natural antioxidants in ground pork patties. Zamuz et al. (2018) indicated that the addition of chestnut by-product extracts to the beef patties had a positive effect on the decrease in the TBARS values, even at the lowest concentrations, especially with leaf and bur extracts.

The findings, however, differ from those reported by Longato et al. (2019), where the application of hazelnut skin as an antioxidant at concentrations of 2–3 % in chicken burgers exhibited a pro-oxidant effect.

3.3.2. *Volatiles profile*

Table 3 reports volatile compounds detected in burgers.

The most important source of aroma compounds is the lipid fraction of meat, which generates acids, aldehydes, ketones, and alcohols through the oxidation of phospholipids. By-products of fat oxidation are short-chain compounds responsible for the aroma and flavor of meat (Lopez-Moreno et al., 2023). In our study, we found 30 main compounds, as shown in Table 3. The difference between the three treatments is extremely noticeable, especially in the HSE samples, which had the lowest production of volatile compounds. When considering the total percentages of the classes of compounds detected, it is clear that the presence of alkanes (HS 3.37 %, HSE 0.65 %) and the low presence of alcohols (HS 11.67 %, HSE 5.25 %) and aldehydes (HS 17.57 %, HSE 13.62 %) in the treated burgers is a sign of an oxidation process blocked in the early stages of degradation, while the absence of alkanes, a moderate presence of alcohols (14.52 %), and a high percentage of aldehydes (48.65 %) in the control burgers indicate that oxidation is in an advanced state. In this group, all the compounds identified as the main indicators of pork meat spoilage, such as hexanal, heptanal, octenal, nonanal, (E)-2-octenal, (E)-2-nonanal, (E,E)-2,4-nonadienal, 1-pentanol, 1-octen-3-ol, and 3 octen-2-one (Liu et al., 2023) were detected. As for the treated samples, they showed either absence or minimal presence of such compounds, except for nonanal, a degradation compound from oleic acid, which is the main fatty acid provided by the hazelnut film. Aldehydes were the most abundant compounds detected in all samples, which is consistent with the literature, as aldehydes occupy the largest proportion (about 40 %) in pork organic compounds, and aldehydes have a relatively low threshold and are volatile, which greatly influences the aroma (Duan et al., 2023). Hexanal, the major compound from the oxidation of n-6 fatty acids, mainly linoleic and arachidonic acid, has been commonly found as the major volatile in the aldehyde group in other research published by authors who have explored the presence of volatile compounds in raw, cured, and cooked meats (Iglesias et al., 2009; Song et al., 2021; Xu et al., 2014). In our case as well, hexanal was the most abundant compound detected, but exclusively in the control samples, highlighting how, in these samples, the oxidative state of lipids led to the formation of characteristic degradation compounds, whereas this was not observed in the treated samples ($P < 0.01$). Regarding alcohols, they are mainly produced by the degradation of linoleic acid and can be divided into saturated and unsaturated alcohols. Unsaturated alcohols have a lower threshold and exert an important impact on the overall flavor. For example, 1-octen-3-ol is an unsaturated alcohol with a low threshold and strong flavor, which may be the main contributor to pork's degraded aroma (Meynier

et al., 1998). In this case too, this compound was significantly higher in the control group ($P < 0.01$). Noteworthy is the presence of an aldehyde, E-15-heptadecenal, in the treated burgers, as this compound was also found in an extract of *Halimeda discoidea* as a bioactive compound capable of inhibiting the growth of *Klebsiella pneumoniae* ATCC, a Gram-negative bacterium associated with diseases such as pneumonia, meningitis, and liver abscess (Supardy et al., 2012).

Based on the results regarding the oxidative state and the oxidation-related volatile compounds in the treated burgers, it is evident that the added powders improved the product's healthiness by enhancing the stability of the lipid fraction during storage and consequently improving the volatile profile developed. The final healthiness of the product is further reinforced by the fact that hazelnut skin does not compromise the microbiological profile of the final product, as confirmed in a previous study (D'Ambra et al., 2023) and that the extract demonstrated antimicrobial activity (Capaldi et al., 2025).

3.4. Color and sensory parameters of burgers

The effect of treatment on color stability of the burger during refrigerated storage is shown in Fig. 2.

During the storage, the HS and HSE groups exhibited better color stability ($P < 0.01$). The delta E values of 3.34 and 1.68 for the HS and HSE samples (Fig. 2), respectively, indicate that the visual changes in the color of the burgers are minimal unlike the control group, which showed visible color changes as explained by Cserhalmi et al. (2006) according to which color changes could be estimated such as noticeable when ΔE values are between 1.5 and 3.0, visible with ΔE of 3.0–6.0, and great between 6.0 and 12.0. It is now known that plant extracts modifying the color of the product tend to cover the loss of gloss and greying of the raw material, making the product more technologically durable while preserving its color characteristics. This ability of natural extracts has also been observed by Šojić et al. (2020) and Zamuz et al. (2018). These studies reported, respectively, that the application of supercritical extracts of wild thyme by-products decreased discoloration in ground pork patties and the application of hull, bur, and leaf chestnut extracts had a positive effect on the color of beef patties during storage.

The effect of treatment on color acceptability and potential for purchase of burgers is shown in Fig. 3.

Even if during storage treatments improved the color preservation, the two treated groups showed a worsening ($P < 0.01$) in terms of color acceptability (Fig. 3). Despite this, the acceptability of the product was not compromised, as the willingness to purchase remained high (Fig. 3). This is because most panelists who rated the color of the burgers as less acceptable but were still inclined toward a potential purchase explained their choice by stating that, if the label or packaging had specified that the coloration was due to the addition of natural plant-based antioxidants, it would not have impacted their decision to buy the product. The same trend about color perception was observed by Turhan et al. (2005) who used hazelnut skin in low-fat beef burgers. The control beef burgers received the highest appearance scores. Increasing the level of hazelnut skin resulted in beef burgers with lower appearance scores and decreased overall acceptability ratings. The same was observed in the study of Al-Juhaimi et al. (2017) in which sensory evaluation of chicken burgers treated with pistachio hull water extracts revealed no significant difference in all sensory attributes between control and treated burgers except color. They observed that the overall mean value for color for the control burger was found to be higher than that of the chicken burger treated with 5 % and 7 % extracts. It is interesting to note that in previous tests on the inclusion of HS in pork burgers (D'Ambra et al., 2023), the evaluation of color by panelists, conducted on cooked burgers, showed results opposite to those of the evaluation on raw burgers carried out in the present study. In fact, when cooked, the burgers with HS tended to receive higher ratings compared to the control, indicating greater appeal.

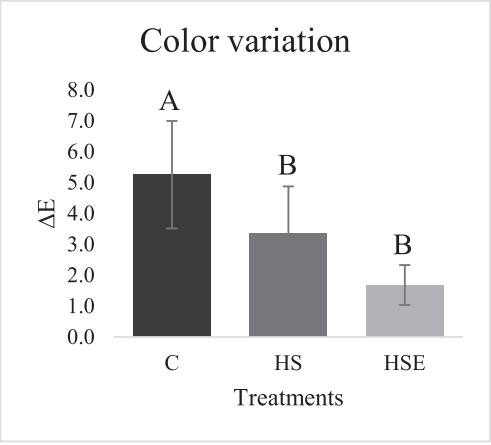

Fig. 2. Impact of treatment on color stability of burgers on the 7th day of storage. C: control burgers; HS: hazelnut skin burgers; HSE: hazelnut skin extract burgers. A, B: different letters indicate statistical differences between groups for $P < 0.01$.

3.5. Tenderness and cooking loss of burgers

The results regarding cooking loss and tenderness of the burgers are reported in Table 4.

Cooking losses were significantly reduced by the addition of the HS at T_0 at T_7 ($P < 0.01$). This confirms the result obtained in the previous study, where HS improved cooking losses (D'Ambra et al., 2023). Our results agree with Turhan et al. (2005), who observed that hazelnut skin added to beef burgers reduced cooking loss and the effect increased as the skin concentration increased. Certainly, this result will be due to the integration of dietary fiber that increases yield and prevents cooking loss in meat-based products by enhancing water-binding capacity, offering significant economic benefits for both consumers and processors (Biswas et al., 2011). Despite lower cooking losses treatments compromised the tenderness of the burgers ($P < 0.01$). The dynamometer results showed that in the HS and HSE groups, the force imparted for maximum deformation was higher respect to C group (Table 4). It is possible that tiny particles or insoluble dietary fibre parts might be filled into the three-dimensional gel net structure of the meat protein available to enhance hardness (Hu et al. 2017). This outcome confirms the results of the sensorial analysis of our previous study, where the burgers with HS had received lower tenderness scores compared to the control group (D'Ambra et al., 2023). An increase in hardness was also observed by Zhao et al. (2021) in low-fat meatballs with kiwi fruit insoluble dietary fiber superfine powder at levels above 3 %.

3.6. Fatty acid composition of burgers

Table 5 reports the effect of treatment on the fatty acid composition of pork burgers.

Only fatty acids and fatty acid classes that showed significant differences between hamburger groups are reported. The addition of hazelnut skin significantly increased the content of monounsaturated fatty acids, mainly due to the increase in oleic acid. This result is consistent with our previous study (D'Ambra et al., 2023), although even though the oleic acid contribution was greater this time, no significant reduction in the omega-6/omega-3 fatty acids ratio was achieved (data not shown in table), unlike in the formulations studied previously.

4. Conclusions

The development and application of natural antioxidants, along with transforming the supply chain into a more sustainable one, are two

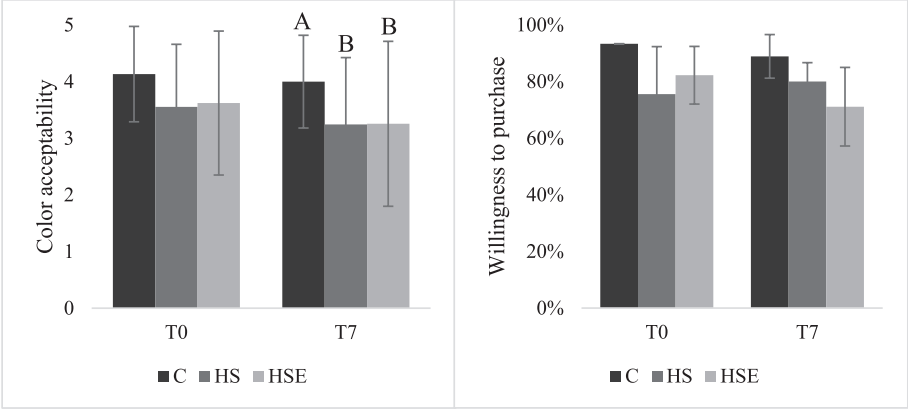

Fig. 3. Influence of treatment on color perception and potential for purchase of burgers. Results are expressed as averages of ratings made by 15 panelists during the three replications of the experiment. C: control burgers; HS: hazelnut skin burgers; HSE: hazelnut skin extract burgers. A, B: different letters indicate statistical differences between groups within each sampling time for $P < 0.01$.

Table 4
Effect of treatment on tenderness and cooking loss of burgers.

	Tenderness (N)		Cooking loss (%)	
	T_0	T_7	T_0	T_7
C	16.9^{B}	19.9^{B}	19.8^{A}	20.4^{A}
HS	24.6^{A}	25.9^{A}	13.4^{B}	13.2^{B}
HSE	23.3^{A}	26.2^{A}	17.5^{A}	17.8^{A}

C: control burgers; HS: hazelnut skin burgers; HSE: hazelnut skin extract burgers. $^{A, B, C}$: different letters on the same column indicate differences for $P < 0.01$.

Table 5
Effect of treatment on fatty acids content (% of total fatty acids detected) of pork burgers.

	C	HS	HSE
C18:1n-9 (oleic)	37.99^{b}	43.95^{a}	37.37^{b}
C18:3n-6 (γ-linolenic)	0.08^{a}	0.03^{b}	0.06^{a}
C20:1 (eicosenoic)	1.09^{a}	0.60^{b}	1.06^{a}
C20:2n-6 (eicosadienoic)	0.67^{a}	0.37^{b}	0.67^{a}
Total monounsaturated	43.45^{b}	49.03^{a}	42.87^{b}

C: control burgers; HS: hazelnut skin burgers; HSE: hazelnut skin extract burgers. $^{a, b, c}$: different letters on the same line indicate differences for $P < 0.05$.

major challenges faced by the meat production and processing industry. The application of hazelnut skin, an important by-product of our agro-industrial chain, and its green phenolic extract demonstrates significant potential as a natural antioxidant in meat products, particularly in improving the oxidative stability of pork burgers. This enhancement in oxidative stability contributes to better preservation of the volatile profile and color of the meat. While minor alterations in sensory attributes, such as color and tenderness, were noted, acceptability remained largely unaffected. In fact, consumer perceptions were positively influenced when they were informed about the natural origin and health benefits of the additives, highlighting the growing demand for clean-label, environmentally sustainable ingredients in food products. These findings emphasize the dual benefits of hazelnut skin as both a functional ingredient and a strategy for upcycling agro-industrial waste. Certainly, there are needs to be explored the development of technologies and processes to efficiently extract and utilize these materials on a commercial scale. Investigating potential barriers to market entry and establishing value chains for these by-products can significantly contribute to reducing waste and promoting sustainability within the agri-food industry.

CRediT authorship contribution statement

Katia D'Ambra: Writing – original draft, Investigation, Formal analysis, Data curation. **Roberta Trovato:** Writing – original draft, Formal analysis, Data curation. **Giovanna Minelli:** Writing – review & editing, Investigation, Data curation. **Alice Cattivelli:** Writing – original draft, Data curation. **Melissa Zannini:** Formal analysis, Data curation. **Davide Tagliazucchi:** Writing – original draft, Investigation, Data curation. **Silvia Tabasso:** Formal analysis, Data curation. **Domenico Pietro Lo Fiego:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Data curation.

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Declaration of competing 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2025.115764.

Data availability

Data will be made available on request.

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