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Lemon co-products as functional ingredients for *mortadella* reformulation: Impact on shelf life, nutritional quality and sensory properties

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ABSTRACT

High consumption of processed meats is associated with higher intakes of refined sugars, sodium, and fats, and lower intakes of phytochemicals and dietary fibres, prompting a search for healthier processed foods. Lemon by-products, which account for up to 50 % of lemon production, are rich in bioactive compounds and represent a promising functional ingredient. This study examined the effects of incorporating lemon dietary fibre (LDF) and/or lemon phenolic compound-rich extract (LPC) recovered from lemon by-products into *mortadella*. Four formulations were developed: Control (CS), LDF (3 %), LPC (1 %), and LDF (3 %) + LPC (1 %). The nutritional, technological, microbiological, phenolic content, and sensory properties of the reformulated *mortadellas* were assessed through shelf-life analysis during 28 days, with sampling at days 0, 7, 14, 21, and 28. Inclusion of LDF significantly ($p < 0.05$) affected moisture, protein, and colour parameters over time. At day 0, the incorporation of LDF increased protein content (16.47 % vs 15.52 % in CS), reduced moisture (62.67 % vs 65.46 % in CS), and enhanced lightness ($L^* = 67.49$ vs 63.62 in CS). Notably, LDF caused a significant reduction in residual nitrite levels ($p < 0.05$), decreasing from 70.50 mg/kg in the control to 36.93 mg/kg at day 0, and from 35.66 mg/kg in the control to 7.85 mg/kg at day 28, indicating its potential to enhance product safety. HPLC analysis confirmed the presence of eriocitrin and hesperidin in the *mortadellas*. Formulations containing LPC, which contains vitamin C, highlight their potential as natural antioxidants to reduce lipid oxidation. Moreover, formulations containing LPC, despite the absence of sodium ascorbate, demonstrated excellent microbiological stability (< 2.5 log cfu/g) over 28 days of storage. Sensory evaluation revealed strong acceptance by panellists, confirming their suitability for use in meat products. Overall, incorporating lemon co-products into *mortadella* provides a practical way to enhance shelf life, nutritional profile, and safety of processed meats.

1. Introduction

The high consumption of red meat, processed meat, and fast food, which is typical in industrialised nations' diets, has been associated with an increased risk of coronary heart disease and other illnesses. These conditions are caused by diets rich in refined sugars, sodium and fats (high in saturated fatty acids) and low in phytochemicals and dietary fibre (Clemente-Suárez, Beltrán-Velasco, Redondo-Flórez, Martín-Rodríguez, & Tornero-Aguilera, 2023). Therefore, meat scientists and industry experts have been developing strategies to produce healthier meat products (Tahmasebi, Labbafi, Emam-Djomeh, & Yarmand, 2016). Depending on particle size, sausage batters or meat emulsions are finely chopped combinations of lean meat, fat, salt, spices, and ice (Kyriakopoulou, Keppler, & Van der Goot, 2021). Some researchers have incorporated bioactive ingredients in processed meat products, such as essential oils (Demirok Soncu, Özdemir, Arslan, Küçükkaya, & Soyer, 2020; Liu & Liu, 2020; Zhang & Piao, 2023), phenolic compounds (PCs) (Balzan et al., 2017; Madani, Choobkar, & Garmakhany, 2023) and dietary fibre (DF) (Henning, Tshalibe, & Hoffman, 2016; Powell, Sebranek, Prusa, & Tarté, 2019; Younis et al., 2022) for nutritional

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enrichment and/or to enhance the shelf life of these products.

Currently, DF consumption in industrialised countries is estimated to be below 25 g per person per day (Pérez-Jiménez, 2024). However, the European Food Safety Authority (EFSA) provides recommendations for adequate dietary fibre intake that vary worldwide and by age group. In general, 25–30 g per day or more is widely recommended for adults (EFSA, 2016). The recommended intakes are delineated as those essential for the maintenance of normal bowel function and cardiovascular health. Nevertheless, emerging evidence indicates that these advantages encompass a broader spectrum, extending beyond these requirements through modulation of the gut microbiota (Venter et al., 2022). Consuming dietary fibre-enriched foods is one approach to increasing fibre intake without drastically changing eating habits, which would be extremely difficult. Currently, many DF-enriched foods are being incorporated into meat products (Han & Bertram, 2017). In addition, dietary fibre also has an important technological role in improving the stability of meat emulsions and is increasingly recognised as a valuable functional ingredient (Zhu et al., 2023).

Some researchers have also explored the biopreservative potential of citrus by-product extracts to enhance the quality of meat and processed meat products. Bambeni et al. (2021) added clementine (*Citrus reticulata*) by-product extracts to raw ground beef patties; the extracts demonstrated potent antibacterial effects, suppressing bacterial growth while also improving aroma intensity, beef-like aroma, and flavour (Bambeni et al., 2021). A recent study by Liu et al. (2025) applied limonene-rich citrus peel extracts from *C. reticulata*, *Citrus sinensis*, *Citrus bigarradia*, and *Citrus macrocarpa* to test their efficacy in preserving beef quality during refrigerated storage: samples treated showed suppressed microbial growth (total bacterial and aerobic counts reduced by 30 %) and reduced lipid oxidation and protein degradation compared to the control samples (Liu et al., 2025). The food industry is continuously seeking alternative solutions for long-term preservation, quality assurance, and safety to meet consumer demand for nutritious and healthy meat-based products (Ghorbani et al., 2024). Oxidative reactions in meat and meat products during storage or cooking degrade colour pigments, lipids, and proteins, leading to a loss of flavour, texture, and nutritional value (Arokiyaraj, Dinakarkumar, & Shin, 2024).

Naturally occurring phenolic compounds, although they are non-nutritional components, are considered promising substances by the meat industry due to their antioxidant, antibacterial, and antifungal properties, which demonstrate their beneficial effects against meat oxidation, spoilage, and foodborne pathogens (Fernandes et al., 2017). At the same time, consumers increasingly favour them for their claimed health benefits (Kalogianni, Lazou, Bossis, & Gelasakis, 2020). Furthermore, ascorbic acid (AA), also known as vitamin C, has been frequently proposed for extending the retail display life of meat. Ascorbic acid has long been recognised for its ability to preserve the colour of raw red meat during storage. On the other hand, depending on its concentration, AA can either promote or inhibit lipid oxidation in muscle foods (Haak, Raes, & De Smet, 2009).

Lemon by-products are of interest to the food industry due to their high levels of nutrients and bioactive compounds (BCs), such as polyphenols, carotenoids, vitamin C, EOs, and dietary fibre, including pectin, cellulose, hemicellulose, and lignin (Magalhães et al., 2023; Nieto et al., 2021; Magalhães, Teixeira and Pintado, 2025). Previous studies have shown that lemon peel (LP) contains higher levels of phenolic compounds and dietary fibre than lemon flesh (Tinh, Sitolo, Yamamoto, & Suzuki, 2021). Structurally, the LP consists of an outer layer, called the epicarp or flavedo, and an inner layer, called the mesocarp or albedo (Xi, Lu, Qun, & Jiao, 2017). The flavedo contains high amounts of phenolic compounds, particularly flavonoids: hesperidin, eriocitrin, diosmin, and narirutin, whereas the albedo is rich in fibres (Klimek-szczykutowicz, Szopa, & Ekiert, 2020; Magalhães et al., 2023; Magalhães et al., 2025).

This study aimed to investigate the effect of adding lemon dietary fibre-based powder (LDF, 3 %) and/or a lemon phenolic compounds-rich extract (LPC, 1 %), both recovered from lemon by-products, on the nutritional quality and sensory properties of *mortadella* (a bologna-type sausage), during a 28 days shelf life study, with sampling every 7 days (days 0, 7, 14, 21, and 28). The novelty of this research lies in the valorisation of lemon co-products, specifically LDF and LPC obtained through an integrated recovery strategy, applied to *mortadella* reformulation. These ingredients were used to fully replace conventional additives, with LDF replacing potato starch and LPC substituting sodium ascorbate.

2. Materials and methods

2.1. Integrative Lemon Functional Ingredients recovery: Lemon phenolic compounds-rich extract (LPC) and Lemon dietary fibre-based powder (LDF)

Lemon co-products were collected and processed according to the method described by Magalhães et al., (2025). Functional ingredients were obtained through an integrative extraction of the Lemon's bioactive fractions. Initially, hydrosol and essential oils were extracted, followed by a phenolic compound-rich lemon extract (LPC) and pectin. The remaining biomass was dried to produce a lemon dietary fibre-based powder (LDF). The LPC was obtained by hydroethanolic extraction (solid-to-solvent ratio 1:9 *m/v*; 60 % ethanol *v/v*) and concentrated sixfold by reverse osmosis (Dellapina et al., 2025); the ethanol was subsequently removed by evaporation before incorporation into *mortadella*. The LDF was previously characterised using the Prosky/Lee methods (AOAC 985.29/991.43) and found to contain 85.8 % total dietary fibre (Lee, Prosky, & de Vries, 1992). To ensure the powder was not perceptible in the *mortadella*, the dried biomass was ground and subjected to granulometric separation, yielding a finely milled powder with particle size below 100 μm (Magalhães et al., 2025).

2.2. Sausage manufacture

Mortadellas were produced following a traditional formula, where the total meat percentage is 100 %, while the percentages of the other ingredients are expressed relative to the meat content. This conventional formula served as a control sample (CS). At the same time, lemon dietary fibre-based powder (LDF) (3 %) and/or lemon phenolic compounds-rich extract (LPC) (1 %) were added to the other samples, as shown in Table 1. To ensure the 3 % of lemon dietary fibre in the *mortadellas*, 3.49 g of LDF was added per 100 g of *mortadellas,* based on the 85.8 % total dietary fibre detected. Furthermore, LDF was used in these innovative reformulated *mortadella* formulations as a replacement for potato starch, based on its water-binding and texturising properties, while increasing the fibre content and contributing to a cleaner-label formulation. LPC was employed as a substitute for sodium ascorbate due to its phenolic composition, which provides natural antioxidant capacity, helping delay lipid oxidation and colour degradation and thereby partially fulfilling the technological role of synthetic additives.

Table 1
Formulation of *mortadellas* with lemon dietary fibre (LDF) at 3 % and lemon phenolic compounds-rich extract (LPC) at 1 %.

	CS	LDF	LPC	LDF + LPC
Lean pork meat %	60	60	60	60
Pork backfat %	40	40	40	40
Water % (ice, *w*/w)	15	15	15	15
Potato starch % (w/w)	3	–	3	–
Sodium chloride % (w/w)	1.5	1.5	1.5	1.5
Sodium tripolyphosphate (mg/kg)	300	300	300	300
Sodium ascorbate (mg/kg)	500	500	–	–
Sodium nitrite (mg/kg)	150	150	150	150
Black pepper %	0.2	0.2	0.2	0.2
Garlic powder %	0.1	0.1	0.1	0.1
Lemon dietary fibre %	–	3	–	3
Lemon phenolic compounds-rich extract %	–	–	1	1

Mortadella-type sausages were produced in the Innovación de Produtos Alimentarios (IPOA) research group pilot plant, employing industrial processing techniques as per the method reported by Magalhães et al. (2025). Three independent batches were produced, each containing five individual sausages (200 g each). Once homogenised, the mixture was stuffed into artificial casing (100 × 150 mm long) (Fibran, Girona, Spain), clipped to separate it into pieces up to 20 cm in length and cooked in a water bath at 85 °C, until the coldest point (the geometric centre of each *mortadella*, corresponding to the thickest part of the product, reached 72 °C (monitored using a thermocouple probe). Once the target temperature was reached, the samples were promptly cooled on ice. After reaching 15 °C, the sausages were vacuum-packed in low density polyethylene bags, with a thickness of 100 μm, and stored at 4 °C until analysis (Fig. 1). Samples from each treatment were taken at days 0, 7, 14, 21, and 28 of storage time and analysed on the same day. Chemical composition and water activity analyses were performed on day 0, while sensory analysis was conducted on both day 0 and day 28. In contrast, all other determinations were performed at all storage time points (0, 7, 14, 21, and 28 days).

2.3. Emulsion stability

The stability of meat batter emulsions (before cooking) was estimated using the total expressible fluid (TEF) method, as described by Botella-Martínez, Viuda-Martos, Angel Pérez-Alvarez, and Fernández-López (2021), with slight modifications (Magalhães et al., 2025). For each determination, 4 *g* of meat batter were centrifuged at 3000 ×*g* for 5 min at 4 °C. Samples were then heated in a water bath at 70 °C for 30 min and cooled to room temperature. After cooling, samples were left standing upside down on filter paper to allow the expressible fluid (fat and water) to be absorbed. TEF was expressed as a percentage of the total fluid expelled relative to the initial sample weight. For each formulation per batch, three determinations were performed.

2.4. Chemical analysis and water activity (a_w)

The proximate composition was measured using the relevant AOAC methods (AOAC International, 2012): moisture (AOAC 925.45), total ash (AOAC 923.03), total lipids (AOAC 991.36), and protein (AOAC 981.10). The water activity (a_w) was determined using an electrolytic hygrometer (Novasina TH-500, Axair Ltd., Pfaeffikon, Switzerland) at 25 °C. These measures were performed in triplicate per batch for each treatment ($n = 9$).

2.5. Technological properties

2.5.1. pH

The pH of *mortadellas* was measured three times in each independent batch using a pH meter (Model 507, Crison, Barcelona, Spain) equipped with a Crison combination electrode probe (Cat. no. 52, Crison, Barcelona, Spain), according to Magalhães et al. (2025). For each formulation per batch, three determinations were performed (n = 9).

2.5.2. Colour

Colour was measured using the CIEL*a*b* colour space with a CM-2600d colourimeter (Minolta Camera Co., Osaka, Japan), as described by Magalhães et al. (2025). The following colour coordinates were determined: lightness (L*), redness (a*), and yellowness (b*). From these coordinates, hue (h*) and chroma (C*) were calculated. Total colour differences (ΔE) of each sample (S) concerning control *mortadella* (C) were also calculated ($\Delta E = (L^*_S - L^*_C)^2 + (a^*_S - a^*_C)^2 + (b^*_S - b^*_C)^2$) ½). Nine determinations were performed per sample, consisting of three measurements on the same inner face of each of three slices (2 cm height).

2.5.3. Textural properties

Texture profile analysis (TPA) was performed with a TA-XT2i Texture Analyser (Stable Micro Systems, Surrey, England). *Mortadella* samples were cut into cubes (1 × 1 × 1 cm) and subjected to a 2-cycle compression test. All instrumental texture analyses were conducted following Magalhães et al. (2025), and the texture profile was determined as described by Bourne (1978). From these curves, the following attributes were calculated: hardness (N), springiness (mm), cohesiveness, and chewiness (N x mm). Six measurements per sample were made.

2.5.4. Residual nitrite level

The residual nitrite level (mg $NaNO_2$/kg sample) was measured using the colourimetric method described in ISO/DIS 2918.26 (1975). Briefly, sample extracts were dissolved in water (10 g/100 mL (*w/v*)) and heated in a boiling water bath (100 °C) for 15 min. After that, 2 mL of Carrez I (Potassium hexacyanoferrate (II) 3-hydrate, PanReac AppliChem, Darmstadt, Germany) and Carrez II (Zinc Acetate 2-hydrate, PanReac AppliChem, Darmstadt, Germany) were added, and the mixture was allowed to stand at room temperature for 30 min. The absorbance of the resulting supernatant was measured after mixing (1:1) with the colourimetric reagent (Griess-Ilosvays nitrite, Merk-Millipore, Darmstadt, Germany) at 520 nm. Measurements were made in triplicate per batch of each formulation ($n = 9$).

2.5.5. Lipid oxidation

For each batch, lipid oxidation was assessed in triplicate by the 2-thiobarbituric acid (TBA) test following the recommendations of Buege and Aust (1978). Briefly, 2.0 g of sample were mixed with 2 mL of 0.5 % (w/v) thiobarbituric acid (TBA) and 2 mL of 10 % (w/v) trichloroacetic acid (TCA) (PanReac AppliChem, Darmstadt, Germany), heated in a boiling water bath (100 °C) for 35 min to develop a pink colour, cooled to room temperature under running tap water, and centrifuged at 5500 rpm for 25 min (Alresa HZ50, Orto Alresa, Aljavit, Madrid, Spain). The absorbance of the resulting supernatant was measured at 532 nm. The thiobarbituric acid reactive substances (TBARs) values were determined using a standard malonaldehyde (MAD) curve and are expressed in mg MAD per kg of sample.

2.6. Determination of phenolic compounds (Eriocitrin and Hesperidin)

2.6.1. Extraction

Samples (2 g) were mixed in Ultraturrax (1 min, 20,000 rpm) with

Fig. 1. Reformulated *mortadellas* with lemon dietary fibre (LDF) and/or lemon phenolic compounds-rich extract (LPC) recovered from lemon by-products.

20 mL of methanol: water (80:20, *v*/v) and then sonicated in an ultrasonic water bath for 12 min at room temperature. After centrifugation (10 min, 8000 *g*, 4 °C), the supernatants were collected, and the pellets were resuspended in 20 mL of acetone: water (70:30, v/v). The exact steps were repeated. Then, the supernatants were combined and evaporated to dryness. Ten millilitres of methanol were added to the residue, and the mixture was thoroughly shaken in a vortex for 2 min. The methanolic extract was filtered through a 0.45 μm filter and stored at −20 °C until analysis.

2.6.2. HPLC analysis

The extraction of phenolic compounds (PCs) was conducted following the methodology described by Genskowsky et al. (2016). To minimise any potential interference from the sugar content in the samples during chromatographic analyses, a C-18 Sep-Pak cartridge was utilised. Before loading the extracts onto the cartridge, it was conditioned with 3 mL of methanol, ultrapure water and hydrochloric acid (10 mM), and subsequently, the cartridge was washed with 3 mL of ultrapure water. The final step involved eluting the cartridge with 3 mL of acidified methanol (0.1 g/L formic acid). The resulting extracts were carefully preserved at −20 °C until HPLC analysis.

Samples (20 μL) were injected into a Hewlett–Packard HPLC series 1200 instrument (Woldbronn, Germany) equipped with UV–Vis Diode Array Detector. Separations were realised on a C_{18} Teknokroma column (Mediterranea sea_{18}, 25 × 0.4 cm, 5 μm particle size; Teknokroma, Barcelona, Spain). The HPLC gradient elution, gradient program, and mobile phases were prepared following Viuda-Martos, Barber, Pérez-Álvarez, and Fernández-López (2015), and the chromatograms were captured at 280, 325, or 360 nm. Phenolic compounds were analysed in both the standard and sample solutions. External standards (Eriocitrin and Hesperidin) were utilised to quantify PCs. Calibration curves were established over the range of 0.1–1 mg/L (Eriocitrin: $y = 569.4\times + 4.6$; Hesperidin: $y = 512.8\times + 36.18$; $R^2 > 0.998$). All analyses were carried out in triplicate for each batch.

2.7. Microbiological analysis

Samples were prepared in a vertical laminar-flow cabinet (model AV 30/70, Telstar, Madrid, Spain). Microbiological analysis of *mortadellas* was carried out in duplicate as follows: for each sample, 10 g was taken and placed in a sterile plastic bag (Sterilin, Stone, Staffordshire, UK) with 90 mL of peptone water (0.1 %). After blending for 1 min in a stomacher blender (Colworth 400, Seward, London, UK), the sample was subjected to serial decimal dilutions, which were then poured into Petri film media (3 M Petrifilm™, Akralab) for the total aerobic bacteria (37 °C for 48 h); *Enterobacteriaceae* (37 °C for 48 h) and yeast and moulds (25 °C for 72 h). The microbiological analysis was conducted at each shelf-life time point (0, 7, 14, 21 and 28 days). Results were displayed as logarithms of colony-forming units per gram (log cfu/g).

2.8. Sensory evaluation

For the sensory evaluation of the four *mortadella* formulations, non-trained panellists (45) (20 males and 25 females) aged 18–60 years, with no specific training in the sensory analysis of *mortadellas*, were recruited from the staff and students at Miguel Hernández University. Prior to testing, participants were informed about the product and study procedures and provided written informed consent. The protocols for sensory analysis were accepted by the Project Evaluation Office of the Miguel Hernández University (OEP, UMH, Elche, Alicante, Spain). This analysis was conducted under white fluorescent lighting, in individual booths. *Mortadella* pieces, each approximately 1.0 cm in height (four pieces, one from each batch), were cut and served at room temperature. The sensory evaluation was conducted between 10:30 a.m. and 2:30 p.m. The samples were coded with a randomised three-digit numerical identifier and served to the panellists on white plates. Unsalted crackers and mineral water (both at room temperature) were provided to cleanse the palate between samples. The hedonic scale comprised 9 levels (1: dislike extremely and 9: like extremely), in which the panellists assessed the following attributes: global appearance, colour appearance, overall quality, hardness, homogeneity, general flavour, acid taste, and bitter taste. Sensory evaluations were conducted at the beginning (day 0) and end (day 28) of storage to assess the samples' initial and final sensory quality.

2.9. Statistical analysis

Conventional statistical techniques were employed to determine means and standard deviations. Data were evaluated by one-way analysis of variance (ANOVA), and if statistically significant differences were found, a Tukey post-hoc test was performed at a 95 % significance level ($p < 0.05$). For the *mortadella* characterisation, ANOVA was applied for each parameter with a one-factor treatment and four levels (control, LDF, LPC, and LDF + LPC). For shelf life determination, an ANOVA with two factors: storage time (0, 7, 14, 21, and 28 days) and treatments (control, LDF, LPC, and LDF + LPC) was applied for each parameter. Principal Component Analysis (PCA) was employed as a multivariate statistical approach to reduce the dataset's dimensionality and investigate the relationships among bioactive compounds, texture, colour, pH, residual nitrite, lipid oxidation, and sensory analysis across different *mortadella* formulations at day 0. The study was based on a data matrix composed of the mean values of the assessed parameters. A biplot was generated to simultaneously illustrate the spatial distribution of the samples and the contribution of each original variable to the principal components. The statistical analyses and PCA were performed using GraphPad Prism Software (version 8).

3. Results and discussion

3.1. Emulsion stability of meat batters

The emulsion stability of *mortadellas* was evaluated on the raw meat before cooking, as shown in Fig. 2. TEF indicates the proportion of fluid separated from the emulsion and serves as a measure of stability. A higher %TEF signifies reduced stability, as more fluid is released, whereas lower %TEF values reflect greater emulsion stability, with minimal fluid separation. The addition of dietary fibre did not result in significant differences ($p > 0.05$) in %TEF values. These results are consistent with findings from various studies, which highlight the benefits of dietary fibre due to its high-water retention capacity and ability to bind both water and fat. These properties improve texture, moisture retention, and fat reduction in food products, making dietary fibre essential for enhancing food formulations (Mishra et al., 2023; Petridis,

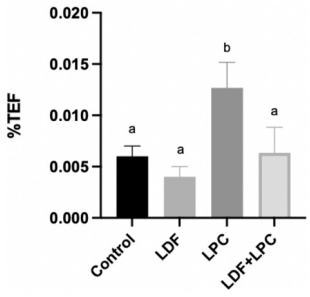

Fig. 2. Effect of incorporation of lemon dietary fibre (LDF) and phenolic compounds-rich extract (LPC) on emulsion stability of *mortadellas*. Results are expressed as % total expressible fluid (%TEF). For each parameter, results followed by the same case letter are not significantly different according to Tukey's HSD post-hoc test ($p > 0.05$). Data are presented as the mean values of replications ± SD.

Raizi, & Ritzoulis, 2014). Therefore, LDF may also be added to meat emulsion products to enhance textural properties and emulsion stability. On the other hand, the addition of phenolic compound-rich extracts to the reformulated *mortadellas* increased the % TEF slightly ($p < 0.05$), probably because the extract was applied in a liquid form. However, in all conditions, all the formulations were stable, as the %TEF was very low. These results align with the normal values for this type of sausage. Jeong and Han (2019) reported that DF has a strong binding capacity for water molecules, thereby reducing the cooking loss and increasing emulsion stability. This study indicates that adding 1 % fruit fibre to sausages minimises water loss by 0.5 % compared to the control group without fibre.

3.2. Chemical composition and water activity (a_w)

The chemical composition of the experimental *mortadellas* is presented in Table 2. Significant differences in protein content ($p < 0.05$) were observed between the control and LDF, LDF and LPC, as well as LPC and LDF + LPC formulations. Notably, the *mortadellas* containing dietary fibre exhibited higher protein content, which can be attributed to the fact that the lemon dietary fibre used contains approximately 5 % protein (Magalhães et al., 2025). These results are auspicious as they indicate an improvement not only in fibre content but also in protein levels within these meat products. For instance, Viuda-Martos, Ruiz-Navajas, Fernández-López, and Pérez-Álvarez (2010) incorporated orange fibre into *mortadellas*, however, no significant differences in protein content were observed between the control (13.1 %) and the orange fibre-enriched *mortadella* (13.09 %). In contrast, findings from García, Dominguez, Galvez, Casas, and Selgas (2002), who added orange fibre to dry fermented sausages, align more closely with our results. This author reported that the control sausage had a protein content of 12.3 %, while the sausage containing 1.5 % orange fibre significantly increased to 17.3 %, reflecting a 5 % rise in protein. Regarding moisture content, significant differences were also found ($p < 0.05$). The inclusion of dietary fibre in both LDF and LDF + LPC formulations contributed to a reduction in moisture levels, with values of 62.67 % and 64.25 %, respectively, compared to the control (65.46 %). This finding is consistent with previous research, as it is well established that citrus dietary fibre is added to meat products for its health benefits, including improved water and fat retention, and enhanced emulsion stability. Regarding fat content and ash, no significant differences were noted across all experimental conditions ($p > 0.05$). Furthermore, a_w was evaluated, and no statistical differences were observed ($p > 0.05$), with values of 0.96 for all samples.

Table 2
Chemical composition and water activity (a_w) of reformulated *mortadellas* with lemon by-products.

Formulation	Moisture (%)	Fat (%)	Protein (%)	Ash (%)	a_w
Control	65.46 ± 0.00^{c}	15.05 ± 0.32^{a}	15.52 ± 0.75^{ab}	2.28 ± 0.00^{a}	0.96 ± 0.00^{a}
LDF	62.67 ± 0.00^{a}	14.70 ± 0.12^{a}	16.47 ± 0.69^{c}	2.17 ± 0.00^{a}	0.96 ± 0.00^{a}
LPC	65.65 ± 0.00^{c}	15.78 ± 0.76^{a}	15.07 ± 0.43^{a}	1.88 ± 0.00^{a}	0.96 ± 0.00^{a}
LDF + LPC	64.25 ± 0.00^{b}	15.10 ± 0.26^{a}	15.98 ± 0.09^{bc}	2.08 ± 0.00^{a}	0.96 ± 0.00^{a}

Control: *mortadella* without lemon by-products; LDF: *mortadella* formulated with LDF at 3 %; LPC: *mortadella* formulated with LPC at 1 %; LDF + LPC: *mortadella* formulated with LDF at 3 % and LPC at 1 %. Values followed by the same letter within the same column are not significantly different ($p > 0.05$), according to Tukey's HSD post-hoc test ($p > 0.05$). Data are presented as the mean values of replications ± SD.

3.3. Physico-chemical analysis during storage study

3.3.1. pH

The pH is a critical parameter for the quality and safety of processed meats such as *mortadella*, influencing key attributes such as texture, flavour, colour, and microbiological stability. Maintaining an optimal pH range of 5.8 to 6.2 is essential for ensuring a smooth and moist texture, effective water retention, and stable fat emulsification. This slightly acidic pH inhibits microbial growth, preserving the product and extending shelf life. In conjunction with preservatives and advanced processing techniques, precise pH control is fundamental to safeguarding product quality and ensuring consumer safety.

The pH values of *mortadellas* were evaluated for 28 days (Table 3). The most acidic pH was observed in the *mortadellas* containing both lemon dietary fibre (LDF) and lemon phenolic compounds-rich extract (LPC), with values ranging from 5.61 to 5.54, which were significantly lower compared to the other formulations. Additionally, on day 0, *mortadella* samples with LDF and LDF + LPC showed significant differences ($p < 0.05$) compared to the control group, a trend that persisted throughout the storage period. This phenomenon can be attributed to the well-known acidity of lemon products, primarily due to their organic acid content, such as citric acid. Despite this acidity, the results for *mortadellas* were well-accepted and aligned with findings from previous studies. For instance, Ibrahim, Hassan, and Hamed (2018) demonstrated similar findings by incorporating lemon peel (LP) powders into meat patties. Their analysis showed that after 15 days of storage, the pH values of raw samples (mixed with 1 % and 2 % of LP) decreased to less than 6.00, reflecting a slight acidity comparable to the current observations in *mortadellas*. Budiarto et al. (2024) conducted a meta-analysis on citrus-derived additives and their effects on the quality and safety of chicken meat. Their findings showed that, on days 2 and 4, citrus additives resulted in a decrease in the pH of the chicken meat compared to the control, with statistical significance ($p < 0.05$). This decrease in pH underscores the acidifying effect of citrus additives, reflecting their consistent impact on meat products. The authors further confirmed the compatibility of lemon-derived ingredients in processed meats, supporting their effectiveness in improving product quality while maintaining safety.

3.3.2. Colour

The colour coordinates represented by L*, a*, b*, C*, and h* are essential components of the CIELAB colour system and its variant, CIE L*C*h*. These systems are widely used to represent colours in a way that more closely aligns with human perception, remaining device-

Table 3
pH shelf life of reformulated *mortadellas* with lemon by-products during 28 days of storage.

	Time (d)				
	0	**7**	**14**	**21**	**28**
Control	5.99 ± 0.06^{aA}	6.01 ± 0.02^{aA}	6.09 ± 0.06^{aB}	5.93 ± 0.02^{aC}	6.03 ± 0.01^{aA}
LDF	5.71 ± 0.04^{bA}	5.68 ± 0.01^{bA}	5.77 ± 0.01^{bBC}	5.72 ± 0.02^{bAC}	5.72 ± 0.03^{bAC}
LPC	5.99 ± 0.02^{aA}	5.92 ± 0.01^{cB}	6.02 ± 0.03^{cA}	5.98 ± 0.00^{aA}	6.01 ± 0.02^{aA}
LDF + LPC	5.61 ± 0.02^{cA}	5.56 ± 0.03^{dA}	5.61 ± 0.03^{dA}	5.59 ± 0.00^{cA}	5.54 ± 0.02^{cB}

Control: *mortadella* without lemon by-products; LDF: *mortadella* formulated with LDF at 3 %; LPC: *mortadella* formulated with LPC at 1 %; LDF + LPC: *mortadella* formulated with LDF at 3 % and LPC at 1 %. For the same compound value followed by the same small letter (a-d) within the same column, it is not significantly different ($p > 0.05$) according to Tukey's Multiple Range Test. For the same compound value followed by the same capital letter (A-C) within the same line, it is not significantly different ($p > 0.05$) according to Tukey's Multiple Range Test. Data are presented as the mean values of replications ± SD.

independent and unaffected by specific lighting conditions. L* represents the lightness of a colour and indicates how light or dark it appears. L* values range from 0 to 100, with 0 representing black and 100 representing white. Redness (a*) denotes the colour position along the green-to-red axis, with negative a* values indicating green and positive values indicating red. At the same time, yellowness (b*) defines the position along the blue-to-yellow axis, with negative values for blue and positive values for yellow. L*, a*, and b* together form the three-dimensional CIELAB model. In the CIE-LCh* variant, colour coordinates are reinterpreted in a cylindrical format. Chroma (C*), or saturation/intensity, represents the purity of colour. Higher C* values indicate more vivid colours. Furthermore, hue angle (h*) defines the colour angle (in degrees) on the colour wheel, from 0° to 360°, identifying the perceived colour category (Sappi Fine Paper North America, 2013).

The colour coordinates of *mortadellas* are shown in Table 4. On day 0, lightness (L*) was significantly ($p < 0.05$) influenced by the fibre content, with the highest L* values observed in LDF + LPC (67.53), followed by LDF (67.49), LPC (63.68), and the control (63.62). This parameter increased over the 28-day storage period, reaching values between 72.25 and 74.23. This increase is likely due to the structural properties of fibre, which consist of macromolecules that rehydrate and remain external to the meat matrix, thereby affecting colour coordinates, particularly lightness. The positive a* values indicate that the mortadellas are closer to the red spectrum, while the positive b* values reflect yellowness. Additionally, fibre content significantly influences yellowness ($p < 0.05$). On day 0, the highest b* value was observed for LDF + LPC (10.26), followed by LDF (10.09), the control (7.92), and LPC (7.62). This order remained consistent throughout the storage period. The values of C* and h* were aligned with the b* values, as the reformulated *mortadellas* containing lemon by-products exhibited higher b* values compared to the control. These results indicate that the samples presented an orange-yellowish hue, with h* values ranging between 67.99 and 71.21 for LDF + LPC, 63.72 and 66.66 for LDF, 61.93 and 69.20 for LPC, and 59.41 and 65.07 for the control. Similarly, the chromatic intensity (C*) was moderate, with values during the 28-day storage period ranging from 11.59 to 14.46 for LDF + LPC, 10.99 to 14.76 for LDF, 8.32 to 11.59 for LPC, and 8.73 to 11.53 for the control. This phenomenon is likely attributed to the composition of LDF, which is derived from lemon peels, a well-known source of yellow pigmentation that influences colour parameters. Our findings align with the study by López-Vargas, Fernández-López, Pérez-Álvarez, and Viuda-Martos (2014), which used albedo-fibre powder derived from yellow passion fruit co-products. Their study concluded that including fibre in raw pork burgers enhances lightness and yellowness. Furthermore, considering the colour differences (ΔE*) concerning the *mortadella* control, it can be said that only the *mortadella* reformulated with lemon phenolic compounds-rich extract (LPC) did not exhibit differences easily detectable by the human eye (< 3 units) (Martínez, Melgosa, Pérez, Hita, & Negueruela, 2001). The other colour differences observed in the *mortadellas* are expected due to the LDF colour, defined as pale yellowish. Nevertheless, the colour of the *mortadella* with LDF and/or LPC, although different from the control, still resembles the typical colour of frankfurter-like sausages, so it should not be a reason for rejection, as fibre and bioactive compounds are essential attributes for consumers, who are increasingly interested in healthy and functional food products.

Table 4
Colour coordinates of *mortadellas* formulated with lemon by-products during 28 days of storage.

		Time (d)				
		0	**7**	**14**	**21**	**28**
L*	Control	63.62 ± 0.25^{aA}	71.26 ± 0.36^{aB}	71.51 ± 0.56^{abB}	71.59 ± 1.36^{aB}	72.42 ± 0.39^{aB}
	LDF	67.49 ± 0.18^{bcA}	71.37 ± 0.80^{aB}	72.82 ± 1.02^{bBC}	72.93 ± 0.38^{aBC}	73.14 ± 0.06^{abC}
	LPC	63.68 ± 0.03^{aA}	70.98 ± 0.31^{aBCDE}	70.48 ± 1.32^{aCD}	71.83 ± 0.47^{aDE}	72.25 ± 0.69^{aE}
	LDF + LPC	67.53 ± 0.31^{cA}	74.04 ± 0.93^{bB}	74.73 ± 0.87^{cB}	74.81 ± 1.18^{bB}	74.23 ± 0.06^{bB}
a*	Control	4.26 ± 0.21^{aA}	5.47 ± 0.18^{aB}	5.64 ± 0.37^{aB}	5.80 ± 0.36^{aB}	5.84 ± 0.13^{abcdB}
	LDF	4.35 ± 0.42^{aA}	6.26 ± 0.46^{bB}	6.49 ± 0.14^{bB}	6.54 ± 0.34^{bB}	6.37 ± 0.02^{bB}
	LPC	3.33 ± 0.09^{bcA}	4.14 ± 0.29^{cBC}	4.55 ± 0.37^{cCD}	5.18 ± 0.07^{aDE}	5.60 ± 0.44^{cdE}
	LDF + LPC	3.51 ± 0.21^{cA}	4.55 ± 0.37^{cBC}	5.23 ± 0.08^{aCDE}	5.36 ± 0.46^{aDE}	5.49 ± 0.13^{dE}
b*	Control	7.92 ± 0.34^{aA}	9.71 ± 0.06^{aBCE}	9.87 ± 0.19^{aCDE}	10.54 ± 0.24^{aDE}	9.88 ± 0.27^{aE}
	LDF	10.09 ± 0.04^{bcA}	13.26 ± 0.50^{bcBCD}	13.65 ± 0.59^{bcCD}	13.30 ± 0.14^{bcD}	12.45 ± 0.35^{bE}
	LPC	7.62 ± 0.46^{aA}	9.97 ± 0.12^{aB}	10.36 ± 0.09^{aB}	10.36 ± 0.31^{aB}	10.35 ± 0.58^{aB}
	LDF + LPC	10.26 ± 0.26^{cA}	13.56 ± 0.48^{cB}	13.43 ± 0.08^{cB}	13.00 ± 0.29^{cB}	13.36 ± 0.29^{cB}
C*	Control	8.73 ± 0.40^{aA}	11.22 ± 0.14^{aB}	11.53 ± 0.31^{aB}	11.62 ± 0.27^{aB}	11.48 ± 0.26^{aB}
	LDF	10.99 ± 0.19^{bA}	14.64 ± 0.47^{bBC}	14.76 ± 0.31^{bB}	14.70 ± 0.25^{bBC}	13.95 ± 0.24^{bC}
	LPC	8.32 ± 0.39^{aA}	11.17 ± 0.06^{aB}	11.66 ± 0.39^{aB}	11.59 ± 0.73^{aB}	11.13 ± 0.20^{aB}
	LDF + LPC	11.59 ± 0.33^{bA}	14.30 ± 0.57^{bB}	14.43 ± 0.08^{b}	13.86 ± 0.26^{c}	14.46 ± 0.24^{bB}
h°	Control	65.07 ± 0.51^{aA}	64.73 ± 1.87^{aA}	59.46 ± 1.46^{aBC}	60.07 ± 1.41^{aC}	59.41 ± 0.78^{aC}
	LDF	66.66 ± 0.65^{abA}	64.91 ± 1.14^{aAB}	63.77 ± 0.87^{bB}	64.79 ± 1.14^{bAB}	63.72 ± 1.20^{bB}
	LPC	67.70 ± 0.76^{abAB}	69.20 ± 1.34^{bcA}	66.24 ± 2.49^{bcB}	61.93 ± 1.25^{aCD}	63.63 ± 0.49^{bD}
	LDF + LPC	69.33 ± 1.45^{bABC}	71.21 ± 1.18^{cAB}	68.59 ± 0.44^{cAC}	69.91 ± 0.58^{cAC}	67.99 ± 1.36^{cC}
ΔE*	Control			–		
	LDF	10.01 ± 2.59^{aA}	7.09 ± 0.92^{aB}	8.47 ± 2.17^{aC}	4.31 ± 0.60^{aD}	5.26 ± 0.81^{aE}
	LPC	0.74 ± 0.22^{bADE}	1.06 ± 0.03^{bB}	0.82 ± 0.47^{bCE}	0.69 ± 0.38^{bD}	0.82 ± 0.33^{bE}
	LDF + LPC	10.82 ± 3.10^{cA}	12.14 ± 3.19^{cB}	11.83 ± 1.71^{cC}	7.99 ± 3.36^{cD}	8.40 ± 2.24^{cE}

Control: *mortadella* without lemon by-products; LDF: *mortadella* formulated with LDF at 3 %; LPC: *mortadella* formulated with LPC at 1 %; LDF + LPC: *mortadella* formulated with LDF at 3 % and LPC at 1 %. For the same compound value followed by the same small letter (a-d) within the same column, is not significantly different ($p > 0.05$) according to Tukey's Multiple Range Test. For the same compound value followed by the same capital letter (A-E) within the same line, it is not significantly different ($p > 0.05$) according to Tukey's Multiple Range Test. Data are presented as the mean values of replications ± SD.

3.3.3. Texture analysis

Table 5 shows the effect of adding lemon functional ingredients on the textural properties (TPA) of *mortadellas*. At day 0, the addition of lemon fibre (both in LDF and LDF + LPC formulations) resulted in a significant increase in the hardness of mortadellas ($p < 0.05$). This improvement is due to lemon fibre particles that are probably integrated into the protein matrix, resulting in better structural binding and increased firmness. Over time, the hardness of these samples decreased. At day 28, only the LDF + LPC (5.56) demonstrated significantly lower hardness values ($p < 0.05$) compared to the other samples, which exhibited comparable values: control (7.27), LDF (7.82), and LPC (8.45). These results suggest a synergistic effect between LDF and LPC in reducing hardness during the storage period. No previous studies evaluating the impact of citrus-derived fibre or polyphenols on the shelf life of *mortadella* texture were found for direct comparison. Nonetheless, related research supports these findings. For example, López-Vargas et al. (2014) reported that adding 5 % passion fruit albedo in raw pork burgers increased the hardness at day 0 (control: 12.31 vs. treated: 18.06). Similarly, Viuda-Martos et al. (2010) observed that incorporating orange dietary fibre and spice oils in *mortadellas* boosted hardness at day 0 (control: 13.90 vs. treated: 16.99–17.03). These studies

Table 5
Textural properties (TPA) of *mortadellas* formulated with lemon by-products during 28 days of storage.

Parameter	Sample	Time (d)				
		0	**7**	**14**	**21**	**28**
Hardness (N)	Control	5.65 ± 0.06^{aA}	6.24 ± 0.77^{aA}	6.78 ± 0.54^{aA}	7.28 ± 0.90^{aA}	7.27 ± 1.28^{abA}
	LDF	8.92 ± 1.20^{bcABC}	5.75 ± 0.56^{abB}	6.69 ± 0.88^{aBC}	7.14 ± 0.71^{aBC}	7.82 ± 1.08^{aC}
	LPC	4.07 ± 0.49^{aA}	4.54 ± 0.34^{abA}	5.14 ± 0.10^{aA}	7.84 ± 1.03^{aB}	8.45 ± 0.91^{aB}
	LDF + LPC	9.11 ± 0.02^{cA}	3.98 ± 0.41^{bBC}	4.01 ± 0.25^{bBC}	6.80 ± 0.32^{aC}	5.56 ± 1.25^{bC}
Cohesiveness	Control	0.77 ± 0.13^{aA}	0.81 ± 0.02^{aA}	0.83 ± 0.03^{aA}	0.81 ± 0.01^{aA}	0.82 ± 0.01^{aA}
	LDF	0.60 ± 0.03^{bA}	0.66 ± 0.07^{bB}	0.67 ± 0.01^{bB}	0.68 ± 0.01^{bB}	0.68 ± 0.04^{bB}
	LPC	0.72 ± 0.05^{aAB}	0.82 ± 0.04^{aB}	0.83 ± 0.03^{aB}	0.80 ± 0.02^{aB}	0.79 ± 0.01^{aB}
	LDF + LPC	0.60 ± 0.03^{bA}	0.64 ± 0.05^{bAB}	0.69 ± 0.04^{bB}	0.64 ± 0.02^{bAB}	0.69 ± 0.07^{bB}
Springiness (mm)	Control	0.17 ± 0.02^{aA}	0.17 ± 0.02^{aA}	0.18 ± 0.01^{aA}	0.17 ± 0.00^{aA}	0.17 ± 0.02^{aA}
	LDF	0.21 ± 0.02^{abA}	0.18 ± 0.04^{aA}	0.17 ± 0.02^{aA}	0.17 ± 0.01^{aA}	0.17 ± 0.02^{aA}
	LPC	0.22 ± 0.02^{bA}	0.17 ± 0.02^{aA}	0.17 ± 0.03^{aA}	0.17 ± 0.03^{aA}	0.18 ± 0.02^{aA}
	LDF + LPC	0.22 ± 0.02^{abABC}	0.17 ± 0.04^{aA}	0.14 ± 0.01^{aB}	0.18 ± 0.02^{aAC}	0.19 ± 0.01^{aC}
Chewiness (g mm)	Control	0.76 ± 0.06^{aA}	0.88 ± 0.11^{aAB}	0.95 ± 0.18^{aAB}	1.05 ± 0.05^{aAB}	1.18 ± 0.06^{aB}
	LDF	0.71 ± 0.10^{acAB}	0.71 ± 0.07^{abAB}	0.54 ± 0.12^{bB}	0.86 ± 0.19^{abAB}	0.91 ± 0.08^{aA}
	LPC	0.79 ± 0.06^{aAD}	0.72 ± 0.17^{abB}	0.60 ± 0.05^{bB}	1.08 ± 0.24^{aCD}	1.18 ± 0.18^{aD}
	LDF + LPC	0.43 ± 0.07^{cA}	0.42 ± 0.23^{bA}	0.43 ± 0.07^{bA}	0.66 ± 0.16^{bA}	0.59 ± 0.13^{bA}

Control: *mortadella* without lemon by-products; LDF: *mortadella* formulated with LDF at 3 %; LPC: *mortadella* formulated with LPC at 1 %; LDF + LPC: *mortadella* formulated with LDF at 3 % and LPC at 1 %. For the same compound value followed by the same small letter (a-c) within the same column, is not significantly different ($p > 0.05$) according to Tukey's Multiple Range Test. For the same compound value followed by the same capital letter (A-D) within the same line, is not significantly different ($p > 0.05$) according to Tukey's Multiple Range Test. Data are presented as the mean values of replications ± SD.

underscore the impact of plant-derived fibres on the initial hardness properties of meat products.

Regarding cohesiveness, the control and LPC formulations exhibited significantly higher values ($p < 0.05$) compared to the formulations containing lemon fibre. This finding suggests that the control and LPC samples possess a more robust internal structure, enabling them to maintain their integrity more effectively when subjected to compression/mastication. Conversely, the lower cohesiveness values observed in lemon fibre samples indicate a weaker structural network, resulting in a greater propensity for these products to break apart or crumble under mechanical stress. These findings align with the chewiness results, as the control and LPC formulations also exhibited higher values for this parameter, demonstrating that these formulations require greater effort to break down during mastication. In contrast, the *mortadellas* containing lemon fibre demonstrated lower chewiness values, suggesting that these samples disintegrate more easily during chewing. Springiness was not affected ($p > 0.05$) by LDF, LPC, or LDF + LPC under different conditions and during the storage period. These outcomes are consistent with those reported by Delgado-Ospina et al. (2022), who incorporated 3 % cocoa shell powder, a fibre-rich ingredient, into their formulations. Their study observed a decrease in both cohesiveness and chewiness compared to the control, aligning with the results obtained in the present study.

3.3.4. Residual nitrite level

Nitrates and nitrites are among the most widely used curing agents in meat products, primarily for their role in preservation, safety, and sensory enhancement. Nitrites provide the distinctive red colour, flavour, and texture of cured meats, including sausages, ham, salami, and *mortadellas*. Beyond their sensory contributions, nitrites serve as antioxidants, protecting against meat lipid oxidation and thereby preventing rancidity (off-flavour). Furthermore, nitrites are essential for food safety due to their bacteriostatic and bactericidal effects. At concentrations of 150 ppm, nitrites are highly effective in inhibiting the growth and toxin production of *Clostridium botulinum*, a bacterium that can cause serious foodborne illnesses. However, reducing residual nitrite levels in processed meats has emerged as a promising approach to lower dietary nitrite intake and mitigate the potential formation of harmful N-nitroso compounds, which carry carcinogenic, teratogenic, and mutagenic risks (Shakil et al., 2022).

The residual nitrite level of reformulated *mortadellas* with lemon by-products is presented in Table 6. All samples exhibited statistically

Table 6
Residual nitrite (mg $NaNO_2$/kg) of *mortadellas* formulated with lemon by-products, during 28 days of storage.

	Time (d)				
	0	**7**	**14**	**21**	**28**
Control (mg/kg)	70.50 ± 0.98^{aA}	58.80 ± 2.41^{aB}	21.32 ± 0.39^{aC}	46.25 ± 3.16^{aD}	35.66 ± 0.42^{aE}
LDF (mg/kg)	36.93 ± 2.21^{bA}	13.65 ± 2.51^{bB}	3.55 ± 0.10^{bC}	6.78 ± 0.00^{bD}	7.85 ± 0.34^{bE}
LPC (mg/kg)	76.59 ± 3.44^{cA}	40.81 ± 2.54^{cB}	26.74 ± 1.54^{cC}	57.88 ± 0.19^{cD}	56.05 ± 1.65^{cE}
LDF + LPC (mg/kg)	47.68 ± 1.85^{dA}	33.56 ± 4.35^{dB}	10.22 ± 1.89^{dC}	25.03 ± 0.07^{dD}	19.15 ± 0.60^{dE}

Control: *mortadella* without lemon by-products; LDF: *mortadella* formulated with LDF at 3 %; LPC: *mortadella* formulated with LPC at 1 %; LDF + LPC: *mortadella* formulated with LDF at 3 % and LPC at 1 %. For the same compound value followed by the same small letter (a-d) within the same column, is not significantly different ($p > 0.05$) according to Tukey's Multiple Range Test. For the same compound value followed by the same capital letter (A-E) within the same line, the differences are not significant ($p > 0.05$) according to Tukey's Multiple Range Test. Data are presented as the mean values of replications ± SD.

significant differences between conditions ($p < 0.05$). This indicates that variations in formulation among the samples led to measurable differences, confirming that changes to specific parameters, such as ingredient composition, had a meaningful impact on the final product attributes during storage. At the beginning of the experiment (day 0), the LDF reduced the residual nitrite levels by nearly 50 %, showing a concentration of 36.93 mg $NaNO_2$/kg, compared to the control at 76.59 mg $NaNO_2$/kg. This reduction persisted throughout the storage period. The residual nitrite level of the reformulated *mortadella* sample with LDF on day 0 is the only one that complies with Regulation (EU) No 2023/2108 of the European Parliament and Council, which establishes a maximum residual level of 45 mg/kg in sausages ready for marketing throughout their shelf life (Official Journal of the European Union, 2023). On day 28, residual nitrite levels in the LDF *mortadella* decreased to 7.85 mg $NaNO_2$/kg, while the control remained higher at 35.66 mg $NaNO_2$/kg. Additionally, on day 28, only the *mortadella* with LPC surpasses the maximum allowable level of residual nitrite. Furthermore, the order of residual nitrite reduction was LDF < LDF + LPC < LPC, indicating that LDF exhibited a higher nitrite reduction capacity than LPC. This enhanced reduction in LDF *mortadella* may be due to the reactive

properties of various bioactive compounds in dietary fibre, mainly phenolic acids and non-extractable phenolic compounds, known as "bound-phenolic compounds", which are reported to interact with nitrites. Numerous studies have highlighted the reactivity of nitrites with phenolic compounds, suggesting that such interactions may contribute to the observed reduction (Ferysiuk & Wójciak, 2020; Riel, Boulaaba, Popp, & Klein, 2017; Xi, Sullivan, Jackson, Zhou, & Sebranek, 2011). For example, Khaleghi, Kasaai, Khosravi-Darani, and Rezaei (2016) suggested an antagonistic effect between the phenolic compounds of barberry extract and nitrite in cooked beef sausage during refrigerated storage. Furthermore, lemon by-products, especially LDF, can be considered a potential ingredient in the meat industry due to their ability to reduce residual nitrite levels, thus helping to prevent the possible formation of N-nitroso compounds.

3.3.5. Lipid oxidation

Lipid oxidation is a chemical process that leads to the deterioration of fats in meat, resulting in rancid flavours, unpleasant odours, and a shorter shelf life. This oxidation process is closely linked to the effects of nitrite, which is commonly used as a preservative in processed meats. Nitrite helps preserve meat by inhibiting the growth of spoilage bacteria and slowing down lipid oxidation. It achieves this by reacting with reactive oxygen species (ROS), such as hydroxyl radicals, which are known to initiate oxidation. The addition of sodium nitrite to meat products significantly reduces TBARs (thiobarbituric acid reactive substances) values, thereby helping to maintain meat quality over time. Furthermore, plant extracts, rich in natural antioxidants, offer additional protection against oxidation.

Table 7 illustrates the effects of adding lemon functional ingredients and storage time on the lipid oxidation of *mortadellas*. At day 0, the LPC treatment exhibited the most effective protection against lipid oxidation, with a 0.08 mg MDA/kg sample. This result aligns with the findings for nitrite content, as the LPC condition had a higher nitrite level compared to the others, which is associated with reduced lipid oxidation. Furthermore, this condition showed a statistically significant effect ($p < 0.05$) compared to the other three conditions. Over time, some fluctuations in lipid oxidation levels were observed. However, on day 28, the LPC formulation continued to demonstrate strong lipid oxidation inhibition, with a final level of 0.06 mg MDA/kg. Furthermore, the reduction of lipid oxidation in LPC *mortadellas* formulations can also be attributed to the presence of vitamin C in the lemon phenolic compounds-rich extract.

Additionally, it is essential to note that lipid oxidation levels in all reformulated *mortadellas* remained below the rancidity threshold (≥1.0) throughout the 28-day storage period. Our study aligns with others in the field. For instance, Deng, Shi, and Xia (2022) created a bacon product containing 300 mg/kg of apple polyphenols and found lower TBARs (0.59 MDA/kg) than the control group. Furthermore, a study conducted by Cava and Ladero (2024) supports this conclusion, showing that in cooked chicken models treated with polyphenol-rich extracts from tropical fruit by-products, the lower TBARs can be attributed to the antioxidant activity of the phenolic compounds and their ability to inhibit lipid oxidation. In conclusion, free polyphenols found in LPC could be a promising natural antioxidant alternative to sodium ascorbate, which is used in *mortadella* control to reduce lipid oxidation while improving the safety of these processed meat products.

Table 7
TBARs values (mg malonaldehyde (MDA)/kg sample) of *mortadellas* formulated with lemon by-products, during 28 days of storage.

	Time (d)				
	0	**7**	**14**	**21**	**28**
Control (mg/kg)	0.27 ± 0.08^{aA}	0.01 ± 0.00^{aB}	0.01 ± 0.00^{aCB}	0.09 ± 0.03^{aD}	0.07 ± 0.03^{aED}
LDF (mg/kg)	0.25 ± 0.08^{aA}	0.19 ± 0.04^{bB}	0.09 ± 0.03^{bCD}	0.12 ± 0.04^{aD}	0.21 ± 0.05^{bEB}
LPC (mg/kg)	0.08 ± 0.02^{bA}	0.01 ± 0.00^{aB}	0.01 ± 0.00^{aCB}	0.04 ± 0.01^{bDB}	0.06 ± 0.00^{aAB}
LDF + LPC (mg/kg)	0.20 ± 0.05^{cA}	0.16 ± 0.02^{cbBCE}	0.10 ± 0.02^{cB}	0.14 ± 0.06^{caDBC}	0.19 ± 0.00^{cbAE}

Control: *mortadella* without lemon by-products; LDF: *mortadella* formulated with LDF at 3 %; LPC: *mortadella* formulated with LPC at 1 %; LDF + LPC: *mortadella* formulated with LDF at 3 % and LPC at 1 %. For the same compound value followed by the same small letter (a-c) within the same column, the differences are not significantly different ($p > 0.05$) according to Tukey's Multiple Range Test. For the same compound value followed by the same capital letter (A-E) within the same line, the differences are not significant ($p > 0.05$) according to Tukey's Multiple Range Test. Data are presented as the mean values of replications ± SD.

3.3.6. Determination of phenolic compounds (Eriocitrin and Hesperidin)

Table 8 presents the phenolic compound content (more specifically, the flavonoid content) in the analysed samples. Across all samples, the only phenolic compounds identified were hesperidin and eriocitrin. Other phenolic compounds initially present in the lemon by-products were gradually lost during the *mortadella* production process. This can be attributed to thermal degradation or transformation, oxidative reactions, and interactions with proteins and lipids. In contrast, eriocitrin and hesperidin, are flavanone glycosides (eriodyctiol-7-O-rutinoside and hesperetin-7-O-rutinoside, respectively), bearing a rutinose unit attached at the C-7 position of the flavonoid nucleus. This glycosidic linkage increases their solubility and may enhance resistance to heat- and oxidation-induced degradation, which likely explains why only these two compounds remained detectable after processing.

At day 0, hesperidin levels were highest in LDF (23.84 μg/g), followed by LDF + LPC (20.57 μg/g) and LPC (2.76 μg/g) ($p < 0.05$). Regarding eriocitrin, LDF + LPC showed the highest concentration (14.85 μg/g), followed by LDF (13.70 μg/g) and LPC (3.74 μg/g). The storage period significantly affects the levels of phenolic compounds (PCs) in processed meats, including hesperidin and eriocitrin. These compounds degrade over time due to environmental factors, including pH, temperature, light exposure, and oxygen. Additionally, interactions with proteins, lipids, and other components within the *mortadella* matrix may transiently mask PCs, reducing their detectability at specific points.

Table 8
Phenolic compounds of *mortadellas* formulated with lemon by-products, during 28 days of storage.

Compound		Time (d)				
		0	**7**	**14**	**21**	**28**
Hesperidin (μg/g)	LDF	23.64 ± 0.34^{aA}	36.25 ± 1.10^{aB}	10.59 ± 0.01^{aC}	25.26 ± 1.07^{aAD}	26.71 ± 0.74^{aD}
	LPC	2.76 ± 0.16^{bA}	4.22 ± 0.04^{bAC}	6.08 ± 0.33^{bBC}	3.00 ± 0.13^{bA}	5.41 ± 0.19^{bC}
	LDF + LPC	20.57 ± 0.57^{cAD}	42.24 ± 1.15^{cB}	7.27 ± 0.46^{bC}	18.92 ± 0.30^{cD}	32.38 ± 0.48^{cE}
Eriocitrin (μg/g)	LDF	13.70 ± 0.21^{aAD}	19.80 ± 0.33^{aBE}	8.35 ± 0.11^{aC}	13.40 ± 0.48^{aD}	19.18 ± 0.39^{aE}
	LPC	3.74 ± 0.11^{bAB}	4.38 ± 0.15^{bBC}	4.65 ± 0.19^{bC}	6.04 ± 0.19^{bD}	1.69 ± 0.08^{bE}
	LDF + LPC	14.85 ± 0.50^{cAE}	31.13 ± 0.93^{cB}	20.56 ± 0.04^{cC}	19.26 ± 0.23^{cD}	15.53 ± 0.28^{cE}

LDF: *mortadella* formulated with LDF at 3 %; LPC: *mortadella* formulated with LPC at 1 %; LDF + LPC: *mortadella* formulated with LDF at 3 % and LPC at 1 %. For the same compound value followed by the same small letter (a-c) within the same column are not significantly different ($p > 0.05$) according to Tukey's Multiple Range Test. For the same compound value followed by the same capital letter (A-E) within the same line, are not significantly different ($p > 0.05$) according to Tukey's Multiple Range Test. Data are presented as the mean values of replications ± SD.

PCs can bind to proteins and fats, forming complexes that fluctuate between bound and free states, further complicating their quantification (Patrón-Vázquez et al., 2019).

Lemon fibre, functioning as both an antioxidant and stabiliser, may play a role in modulating phenolic bioaccessibility and reorganising the food matrix. This could account for observed PC-level fluctuations, including initial increases, subsequent decreases, and later rebounds. Furthermore, the water absorption properties of lemon fibre, alongside its interactions with other compounds, can influence the release and bioavailability of phenolics, thereby affecting their measured concentrations over time. The study conducted by Viuda-Martos et al. (2010) also reported significant differences ($p < 0.05$) in hesperidin recovered from citrus fibre in *mortadellas* during the 24-day storage period.

3.4. Microbiological analysis

The microbiological analysis was performed for 28 days (Days 0, 7, 14, 21, and 28) for total aerobic bacteria, *Enterobacteriaceae*, yeast and moulds. The microorganisms analysed were not detected (< 2.5 log cfu/g) in any of the conditions for 28 days, except for total aerobic bacteria, which were found at 2.7 log cfu/g on day 28 in the control. The pH of around 6.0 and the heat treatment, as well as storage at 4 °C, seem to be sufficient to produce a microbiologically stable product that remains stable for at least 28 days of storage. This microbiological stability in the case of reformulated *mortadellas* with LDF and LPC can be associated with the presence of phenolic compounds. These compounds are well-documented as natural antioxidants and antimicrobial sources recovered from lemon by-products (Papuc, Goran, Predescu, Nicorescu, & Stefan, 2017; Saleem et al., 2023).

3.5. Sensory analysis

Evaluating sensory quality is crucial due to the distinct acidic and bitter flavours present in citrus products. Sensory evaluations were conducted only on days 0 and 28, as the most pronounced and persistent sensory differences were expected to emerge toward the end of storage, when cumulative processes such as oxidation, nitrite depletion, and microbial activity are most evident. Intermediate instrumental and microbiological measurements (colour, TBARs, residual nitrite and microbial counts) were taken at days 7, 14 and 21 to characterise the trajectory of these changes and to help interpret the endpoint sensory result.

Fig. 3 shows the results obtained for the sensory analysis carried out at the beginning (day 0) and end (day 28) of the experiment for global appearance (overall visual impression: texture, colour, homogeneity), colour appearance, general quality, hardness, homogeneity, flavour general, acid taste, and bitter taste. The panellists evaluated these parameters on a hedonic scale of 9 levels (1: dislike extremely and 9: like extremely).

Regarding the differences observed in global appearance, at day 0, significant differences ($p < 0.05$) were found among all conditions. At day 28, however, no differences were detected between Control vs. LPC and LDF vs. LPC. Comparing day 0 vs. day 28, only the Control condition showed no significant differences ($p > 0.05$).

For colour appearance, at day 0, all samples exhibited significant differences ($p < 0.05$). However, on day 28, differences were not observed between Control vs. LDF and LDF vs. LPC. Over time, only the LDF showed significant differences ($p < 0.05$). Although instrumental colour measurements revealed significant differences among treatments, these variations were not noticed by the sensory panel for all samples. The minimal extent of the instrumental colour changes likely explains why the sensory panel did not perceive these differences. Additionally, factors such as lighting conditions during evaluation, sample presentation, and individual differences in colour perception may have influenced the lack of alignment between instrumental and sensory results. During the sensory analysis, panellists rated the samples using a 9-point hedonic scale, where 1 meant “dislike extremely” and 9 meant “like extremely”. This assessment aimed to determine the degree of consumer acceptance, rather than to identify statistically significant differences between samples.

Regarding general quality, at day 0, all conditions were significantly different except for LDF vs. LDF + LPC. By day 28, only the Control vs. LPC condition showed no differences ($p > 0.05$). When comparing day 0 and day 28, significant differences ($p < 0.05$) were observed only for the control.

For hardness, on day 0 and day 28, there were no differences between LDF and LDF + LPC. Furthermore, when comparing storage times, no significant differences ($p > 0.05$) were found among any of the conditions. On day 0, sensory evaluation results were consistent with the TPA findings for the hardness parameter, both indicating higher hardness in the LDF and LDF + LPC samples. By day 28, panellists continued to perceive these samples as harder. However, TPA measurements revealed no significant differences among the control, LDF, and LPC samples. Only the LDF + LPC sample differed significantly ($p < 0.05$), exhibiting lower hardness values. Regarding homogeneity, no significant differences were observed at day 0 or day 28 between Control vs.

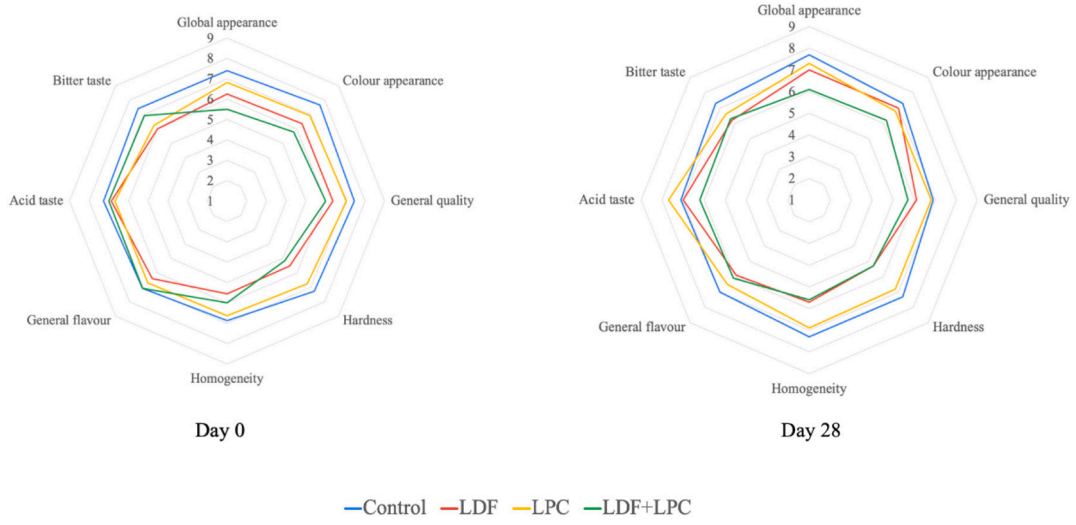

Fig. 3. Sensory evaluation on day 0 (start of experiment) and day 28 (end of experiment): quantitative descriptive analysis was carried out on the different *mortadellas* reformulated with lemon by-products.

LPC and LDF vs. LDF + LPC. Additionally, comparing storage times, no differences were detected for any conditions ($p > 0.05$).

For general flavour, significant differences were observed at day 0 between Control vs. LDF and LDF vs. LDF + LPC. On day 28, differences were observed across all conditions except LDF + LPC. Comparing storage times, significant differences ($p < 0.05$) were found only for LDF and LDF + LPC. This finding aligns with the lipid oxidation results, as higher oxidation levels were detected in *mortadella* containing the LDF ingredient, which may explain the lower consumer preference observed for this sample in general flavour.

Regarding acidic taste, significant differences were observed on day 0 between Control vs. LPC, while on day 28, differences were detected across all conditions except Control vs. LDF. Significant differences ($p < 0.05$) were observed only for the Control and LDF conditions when comparing the two time points. No significant differences were found at day 0 between LDF vs. LPC for bitter taste. On day 28, the conditions LDF vs. LPC, LDF vs. LDF + LPC, and LPC vs. LDF + LPC showed no significant differences ($p > 0.05$). Significant differences ($p < 0.05$) were observed only for LDF + LPC when comparing storage times. Furthermore, when comparing these results with pH findings, by day 28, the panellists preferred the less acidic LPC sample over the others. This indicates that during storage, panellists started to detect acidic flavours in the *mortadella* samples, favouring the LPC and control formulations. Nevertheless, at day 0, pH did not appear to influence consumer preference significantly.

Additionally, based on these results, the panellists well-received our reformulated *mortadellas.* In terms of general quality and texture, consumers showed a preference for the Control and LPC, followed by LDF and LDF + LPC. Furthermore, the consumers responded positively to the acidic and bitter taste characteristics of lemon-derived products in our reformulated *mortadellas*. This study stands out from others as it uniquely evaluates the sensory properties of *mortadellas* at day 28, demonstrating that our products remain safe for consumption and retain a good appearance at this stage. Microbiological analysis corroborated these findings, as all tested microorganisms (TAB, *Enterobacteriaceae,* yeast, and moulds) at the end of storage remained well below the recommended limit for processed meat products (5 log cfu/g) (Instituto Nacional de Saúde Doutor Ricardo Jorge, 2019), with the highest value observed for TAB in the control sample on day 28 (2.7 log cfu/g). These low microbial levels are consistent with the absence of typical spoilage indicators (high viscosity, colour changes, off-flavours). This interpretation is further supported by the lipid oxidation results, which remained below the rancidity threshold (≥ 1 mg MDA/kg), thereby confirming the microbiological and oxidative stability of the samples throughout the 28-day storage period.

Moreover, a recent meta-analysis by Budiarto et al. (2024) comprehensively evaluated the impact of citrus-derived additives on the quality and safety of chicken meat. These findings are consistent with our study, in which consumers positively evaluated the treated samples, particularly regarding sensory quality and perceived safety. Hedonic testing revealed diverse preferences, with notable improvements in flavour, juiciness, and overall acceptability after storage. Moreover, the meta-analysis strongly advocates the use of citrus additives to maintain the quality and safety of meat products.

3.6. Principal component analysis (PCA)

Principal component analysis (PCA) was employed to integrate and visualise the relationship between texture, colour, pH, lipid oxidation, residual nitrites, and the sensory properties of the *mortadella* formulations at day 0. The objective was to better understand how the bioactive compounds (lemon phenolic compounds-rich extract (LPC) and lemon dietary fibre (LDF)) recovered from lemon by-products can influence the quality of *mortadella.* Fig. 4 illustrates the spatial distribution of the treatments within the two-dimensional space delineated by the initial two principal components. The first component (PC1) accounted for 70.82 % of the total variation, while the second component (PC2) explained 18.46 %, together representing 89.27 % of the observed variability. Control samples (blue ellipse) were positioned on the negative sides of both PC1 and PC2 axes, indicating a positive correlation with sensory parameters such as global appearance, homogeneity, overall flavour, bitterness, and acidity. Conversely, they showed negative associations with lipid oxidation and instrumental hardness. The LPC samples (orange ellipse), positioned in the upper left quadrant, showed a positive correlation with variables such as pH and residual nitrite content ($NaNO_2$), and were distant from the lipid oxidation vector, suggesting that LPC does not promote oxidative degradation in *mortadella*. In contrast, LDF (red ellipse) and LDF + LPC (green ellipse) samples were strongly influenced by the phenolic compounds (eriocitrin and hesperidin), indicating efficient migration and retention of bioactives from the extract into the meat matrix. Moreover, LDF + LPC samples were correlated with both instrumental texture (hardness) and lightness.

Furthermore, the observed differences in spatial distribution among

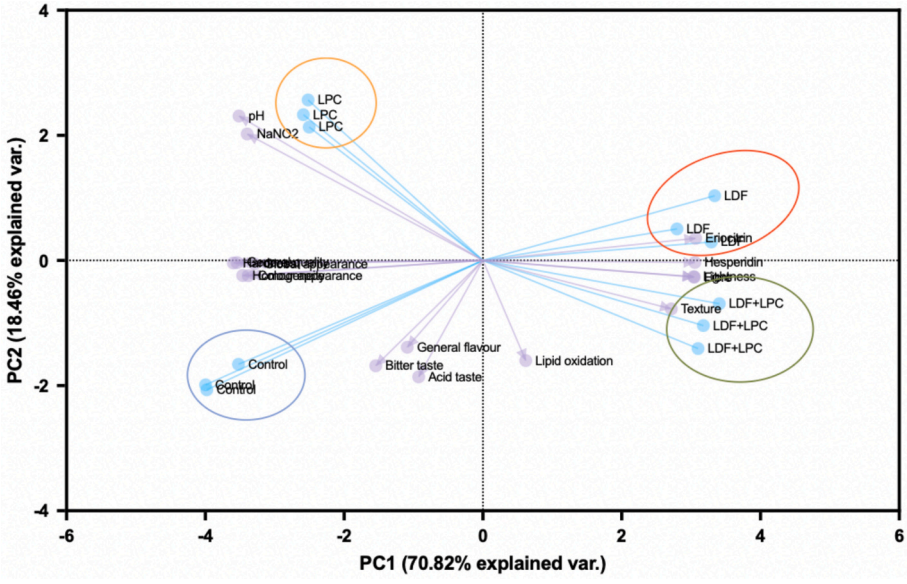

Fig. 4. Principal component analysis (PCA) biplot and component loadings (evaluated parameters) at day 0.

the reformulated samples were driven by the type of lemon-derived functional ingredient employed. LPC contributed to delaying lipid oxidation and improved texture along with a more appealing colour, whereas LDF was more successful in lowering residual nitrite levels. This analysis offers a deeper insight into how these ingredients behave and their roles, which supports their potential for future applications and reinforces their prospects in developing cleaner-label, health-focused meat products.

3.7. Overall comparison with previous preservation/shelf life studies in meat products

To contextualise the present results, we compared this study with previously reported preservation and shelf-life research on meat products, focusing on phenolic content, storage stability, physicochemical changes and sensory traits.

Bermúdez-Gómez et al. (2025) evaluated the effects of reducing sodium and starch on the nutritional, physicochemical, and sensorial properties of *mortadella* made with mushroom stem flour by-products. Although this study did not include microbiological analyses or assess changes during storage, its findings, similar to ours, indicate that replacing sodium and starch with natural ingredients can improve the technological and nutritional quality of *mortadella*, supporting a more sustainable and healthier alternative for the meat sector. Powell et al. (2019) evaluated the substitution of sodium tripolyphosphate with three levels of citrus fibre (0.5 %, 0.75 %, and 1 %) in alternatively cured all-pork Bologna sausage during 98 days of storage at 0–1 °C. Some results are similar to our observations; for example, hardness (N) increased at the 1 % citrus fibre level compared to the control, while sensory panels demonstrated reported good acceptance, with no significant differences ($p > 0.05$) in aroma, flavour, off-flavour, or colour. Tayengwa et al. (2020) incorporated *Citrus reticulata* by-products into raw ground beef patties and compared them with negative (no extract) and positive (sodium metabisulfite) controls during simulated retail display conditions (4 °C) for 9 days. They reported notable antibacterial and chelating activity, attributed to ascorbic acid, flavonoids, terpenoids and limonoids. Consistent with our observations, TBARs increased over time during retail display, likely due to prolonged exposure to pro-oxidants in beef patties.

Furthermore, our study offers several key advancements over previous research. It introduces innovations that address specific gaps by incorporating two functional ingredients: lemon dietary fibre and lemon phenolic compounds-rich extract, both obtained through an integrated valorisation strategy. These compounds were employed to achieve the complete replacement of potato starch and sodium ascorbate, respectively. In contrast to earlier studies, which have predominantly focused on partial reductions or substitutions of individual ingredients, this research implements a total substitution of both ingredients. Furthermore, unlike many preceding works, the present research provides a detailed evaluation of the effects of the two lemon by-product ingredients, alone and combined, and an extensive evaluation of storage stability and a 28-day refrigerated shelf-life. Consequently, this research provides a more holistic and rigorous contribution to the field, effectively addressing several critical gaps identified in previous studies concerning the preservation of meat products.

4. Conclusion

In conclusion, this research demonstrated that reformulating *mortadella* with lemon dietary fibre-based powder effectively boosts its fibre content and replaces potato starch, while also lowering residual nitrite levels compared to the control. Additionally, adding a phenolic compound-rich extract offers a natural alternative to sodium ascorbate as an antioxidant, significantly reducing lipid oxidation. These findings were validated through High-Performance Liquid Chromatography (HPLC) analysis, which identified the naturally occurring phenolic compounds hesperidin and eriocitrin present in citrus. The presence of these bioactive compounds contributed to the observed improvements in the reformulated *mortadellas*. This approach enhances the nutritional profile while preserving technological and visual qualities, thus increasing consumer acceptance. Additionally, it prolongs shelf life by up to 28 days. Sensory evaluations demonstrated that the functional ingredients derived from Lemon were well received by panellists, underscoring the potential of lemon by-products in the innovation of meat products. Future research should incorporate in vitro gastrointestinal digestion assays to assess the bioaccessibility and bioavailability of lemon-derived components. Investigating their prebiotic effects and influence on gut microbiota modulation would also represent valuable directions for further research. Additionally, future work should involve direct comparisons with widely used commercial salt replacers to better understand the potential of lemon by-products as clean-label alternatives in meat products.

Authors contribution

The authors confirm that the manuscript is original, has not been published previously, and is not under consideration for publication elsewhere. All authors contributed significantly to the conception, design, data collection, analysis, and interpretation of the study, and all have approved the final version of the manuscript. The authors declare that there are no conflicts of interest. All experimental procedures complied with the relevant ethical guidelines.

CRediT authorship contribution statement

Daniela Magalhães: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Clara Muñoz Bas:** Writing – review & editing, Visualization, Methodology, Investigation. **M. Viuda-Martos:** Writing – review & editing, Visualization, Validation, Investigation. **J.A. Pérez-Álvarez:** Writing – review & editing, Visualization, Validation, Investigation. **Paula Teixeira:** Writing – review & editing, Visualization, Validation, Supervision, Investigation, Conceptualization. **Manuela Pintado:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

Informed consent statement

Informed consent was obtained prior to conducting experiments involving human subjects. Participants in the sensory analysis initially sign a document indicating their consent to participate in the study.

Institutional review board statement

The sensory analysis of this research article was conducted ethically and following the Guideline for Ethical and Professional Practices for the Sensory Analysis of Foods established by the Institute of Food Science and Technology (IFST), evaluated and supported by the Ethical Committee of Miguel Hernandez University (reference number 2019.07.31 FPRL).

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Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data presented in this study are available upon request from the corresponding author due to privacy concerns.

References

AOAC International. (2012). *Official methods of analysis of AOAC International*. Gaithersburg, Md: AOAC International.

Arokiyaraj, S., Dinakarkumar, Y., & Shin, H. (2024). A comprehensive overview on the preservation techniques and packaging of processed meat products: Emphasis on natural derivatives. *Journal of King Saud University, Science, 36*(1), Article 103032. https://doi.org/10.1016/j.jksus.2023.103032

Balzan, S., Taticchi, A., Cardazzo, B., Urbani, S., Servili, M., Di Lecce, G., … Fasolato, L. (2017). Effect of phenols extracted from a by-product of the oil mill on the shelf-life of raw and cooked fresh pork sausages in the absence of chemical additives. *LWT, 85*, 89–95. https://doi.org/10.1016/j.lwt.2017.07.001

Bambeni, T., Tayengwa, T., Chikwanha, O. C., Manley, M., Gouws, P. A., Marais, J., … Mapiye, C. (2021). Biopreservative efficacy of grape (Vitis vinifera) and clementine mandarin orange (Citrus reticulata) by-product extracts in raw ground beef patties. *Meat Science, 181*, Article 108609. https://doi.org/10.1016/j.meatsci.2021.108609

Bermúdez-Gómez, P., Muñoz-Tébar, N., Martínez-Navarrete, G., Lucas-Gonzalez, R., Pérez-Clavijo, M., Fernández, E., Fernández-López, J., & Viuda-Martos, M. (2025). Effect of sodium and starch reduction on nutritional, physicochemical, and sensorial properties of mortadella added with Agaricus bisporus and Pleurotus ostreatus by-products. *Meat Science, 228*, Article 109888. https://doi.org/10.1016/j.meatsci.2025.109888

Botella-Martínez, C., Viuda-Martos, M., Angel Pérez-Alvarez, J., & Fernández-López, J. (2021). Oil and buckwheat flour and its impact on the chemical, technological and sensory properties of frankfurters. *Foods, 10*(1681). https://doi.org/10.3390/foods10081681

Bourne, M. C. (1978). Texture profile analysis. *Food Technology, 32*, 62–72.

Budiarto, R., Ujilestari, T., Rumhayati, B., Adli, D. N., Hudaya, M. F., Sitaresmi, P. I., … Sholikin, M. M. (2024). Meta-analysis of citrus-derived additives on chicken meat quality and safety: A comprehensive evaluation of acceptability, physicochemical properties, and microbial contamination. In *, Vol. 103, Issue 5*. *Poultry science*. Elsevier Inc.. https://doi.org/10.1016/j.psj.2024.103556

Buege, J. A., & Aust, S. D. (1978). Microsomal lipid peroxidation. *Methods in Enzymology, 52*, 302–310.

Cava, R., & Ladero, L. (2024). Using polyphenol-rich extracts from tropical fruit byproducts to control lipid and protein oxidation in cooked chicken models. *European Food Research and Technology*. https://doi.org/10.1007/s00217-024-04577-x

Clemente-Suárez, V. J., Beltrán-Velasco, A. I., Redondo-Flórez, L., Martín-Rodríguez, A., & Tornero-Aguilera, J. F. (2023). Global impacts of Western diet and its effects on metabolism and health: A narrative review. *Nutrients, 15*(12). https://doi.org/10.3390/nu15122749

Delgado-Ospina, J., Lucas-González, R., Viuda-Martos, M., Fernández-López, J., Pérez-Álvarez, J.Á., Martuscelli, M., & Chaves-López, C. (2022). Potential of the cocoa shell to improve the quality properties of a burger-like meat product. *Journal of Food Processing & Preservation, 46*(8). https://doi.org/10.1111/jfpp.16752

Dellapina, G., Poli, G., Moscatelli, V., Magalhães, D., Vilas-Boas, A. A., & Pintado, M. (2025). Flavonoid-rich extracts from lemon and orange by-products: Microencapsulation and application in functional cookies. *Foods, 14*(19), 3346. https://doi.org/10.3390/foods14193346

Demirok Soncu, E., Özdemir, N., Arslan, B., Küçükkaya, S., & Soyer, A. (2020). Contribution of surface application of chitosan–thyme and chitosan–rosemary essential oils to the volatile composition, microbial profile, and physicochemical and sensory quality of dry-fermented sausages during storage. *Meat Science, 166*. https://doi.org/10.1016/j.meatsci.2020.108127

Deng, S., Shi, S., & Xia, X. (2022). Effect of plant polyphenols on the physicochemical properties, residual nitrites, and N-nitrosamine formation in dry-fried bacon. *Meat Science, 191*. https://doi.org/10.1016/j.meatsci.2022.108872

EFSA. (2016). Scientific opinion on dietary reference values for carbohydrates and dietary fibre. *EFSA Journal, 8*(3), 1–77. https://doi.org/10.2903/j.efsa.2010.1462

Fernandes, R. P. P., Trindade, M. A., Tonin, F. G., Pugine, S. M. P., Lima, C. G., Lorenzo, J. M., & De Melo, M. P. (2017). Evaluation of oxidative stability of lamb burger with Origanum vulgare extract. *Food Chemistry, 233*, 101–109. https://doi.org/10.1016/j.foodchem.2017.04.100

Ferysiuk, K., & Wójciak, K. M. (2020). Reduction of nitrite in meat products through the application of various plant-based ingredients. *Antioxidants, 9*(8), 711. https://doi.org/10.3390/antiox9080711

García, M. L., Dominguez, R., Galvez, M. D., Casas, C., & Selgas, M. D. (2002). Utilization of cereal and fruit fibres in low fat dry fermented sausages. *Meat Science, 60*(3), 227–236. https://doi.org/10.1016/S0309-1740(01)00125-5

Genskowsky, E., Puente, L. A., Pérez-Álvarez, J. A., Fernández-López, J., Muñoz, L. A., & Viuda-Martos, M. (2016). Determination of polyphenolic profile, antioxidant activity and antibacterial properties of maqui [Aristotelia chilensis (Molina) Stuntz] a Chilean blackberry. *Journal of the Science of Food and Agriculture, 96*(12), 4235–4242. https://doi.org/10.1002/JSFA.7628

Ghorbani, A., Mahmoudifar, K., Shokri, S., Mazaheri, Y., Shamloo, E., Rezagholizade-shirvan, A., & Elhamirad, A. H. (2024). Effect of Allium Jesdianum's extract on the physicochemical, antioxidant, antimicrobial and sensory properties of sausage characteristics. *Food Chemistry, 22*, Article 101461. https://doi.org/10.1016/j.fochx.2024.101461

Haak, L., Raes, K., & De Smet, S. (2009). Effect of plant phenolics, tocopherol and ascorbic acid on oxidative stability of pork patties. *Journal of the Science of Food and Agriculture, 89*(8), 1360–1365. https://doi.org/10.1002/jsfa.3595

Han, M., & Bertram, H. C. (2017). Designing healthier comminuted meat products: Effect of dietary fibers on water distribution and texture of a fat-reduced meat model system. *Meat Science, 133*, 159–165. https://doi.org/10.1016/j.meatsci.2017.07.001

Henning, S. S. C., Tshalibe, P., & Hoffman, L. C. (2016). Physico-chemical properties of reduced-fat beef species sausage with pork back fat replaced by pineapple dietary fibres and water. *LWT, 74*, 92–98. https://doi.org/10.1016/j.lwt.2016.07.007

Ibrahim, M., Hassan, I., & Hamed, A. (2018). Application of lemon and orange peels in meat products: Quality and safety. *International Journal of Current Microbiology and Applied Sciences, 7*(04), 2703–2723. https://doi.org/10.20546/ijcmas.2018.704.309

Instituto Nacional de Saúde Doutor Ricardo Jorge. (2019). Interpretação de resultados de ensaios microbiológicos em alimentos prontos para consumo e em superfícies do ambiente de preparação e distribuição alimentar: valores-guia. http://repositorio.insa.pt//handle/10400.18/5610.

ISO/DIS 2918.26, I. S. 2918. (1975). *Meat and Meat Products: Determination of Nitrite Content. Ref. no. ISO 2918:1975*. Genevè: International Organization for Standardization.

Jeong, Y., & Han, Y. (2019). Effect on the emulsification stability and quality of emulsified sausages added with Wanggasi-Chunnyuncho (Opuntia humifusa f. Jeollaensis) fruit powders. *Food Science of Animal Resources, 39*(6), 953–965. https://doi.org/10.5851/kosfa.2019.e85

Kalogianni, A. I., Lazou, T., Bossis, I., & Gelasakis, A. I. (2020). Natural phenolic compounds for the control of oxidation, bacterial spoilage, and foodborne pathogens in meat. *Foods, 9*(6), 1–28. https://doi.org/10.3390/foods9060794

Khaleghi, A., Kasaai, R., Khosravi-Darani, K., & Rezaei, K. (2016). Combined use of black barberry extract and nitrite in cooked beef sausages during the refrigerated storage. *Journal of Agricultural Science and Technology, 18*, 601–614.

Klimek-szczykutowicz, M., Szopa, A., & Ekiert, H. (2020). Citrus Limon (lemon) phenomenon—A review of the chemistry, pharmacological properties, applications in the modern pharmaceutical, food, and cosmetics industries, and biotechnological studies. *Plants, 9*(1). https://doi.org/10.3390/plants9010119

Kyriakopoulou, K., Keppler, J. K., & Van der Goot, A. J. (2021). Functionality of ingredients and additives in plant-based meat analogues. *Foods, 10*(600).

Lee, S. C., Prosky, L., & de Vries, J. W. (1992). Determination of total, soluble, and insoluble dietary fiber in foods—Enzymatic-gravimetric method, MES-TRIS buffer: Collaborative study. *Journal of AOAC International, 75*(3), 395–416. https://doi.org/10.1093/jaoac/75.3.395

Liu, C., Xu, S., Liu, X., Wang, W., Liao, W., Yang, X., & He, Q. (2025). Preservation of beef with limonene-rich citrus peel extracts: Antioxidant, antimicrobial and textural benefits. *Foods, 14*(20), 3506. https://doi.org/10.3390/foods14203506

Liu, T., & Liu, L. (2020). Fabrication and characterization of chitosan nanoemulsions loading thymol or thyme essential oil for the preservation of refrigerated pork. *International Journal of Biological Macromolecules, 162*, 1509–1515. https://doi.org/10.1016/j.ijbiomac.2020.07.207

López-Vargas, J. H., Fernández-López, J., Pérez-Álvarez, J.Á., & Viuda-Martos, M. (2014). Quality characteristics of pork burger added with albedo-fiber powder obtained from yellow passion fruit (Passiflora edulis var. flavicarpa) co-products. *Meat Science, 97*(2), 270–276. https://doi.org/10.1016/j.meatsci.2014.02.010

Madani, A., Choobkar, N., & Garmakhany, A. D. (2023). Determination of phenolic compounds and their antioxidant activity of Iranian Allium sativum controversum extracts and their antimicrobial properties in fresh sausages. *Food Science & Nutrition, 11*(1), 274–283. https://doi.org/10.1002/fsn3.3059

Magalhães, D., Rodrigues, C. V., Botella-Martinez, C., Muñoz-Tebar, N., Angel Pérez-Álvarez, J., Viuda-Martos, M., … Pintado, M. (2025). Lemon dietary fibre-based powder as a promising ingredient for the food industry: Enhancing mortadella nutritional quality. *Foods, 14*, 1693. https://doi.org/10.3390/foods14101693

Magalhães, D., Teixeira, P., & Pintado, M. (2025). Zero waste integrative approach: Recovery of bioactive compounds from lemon by-products. In *Resource recycling and Management of Food Waste* (pp. 415–423). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-86688-3_19.

Magalhães, D., Vilas-Boas, A. A., Teixeira, P., & Pintado, M. (2023). Functional ingredients and additives from lemon by-products and their applications in food

preservation: A review. *Foods, 12*(5), 1095. https://doi.org/10.3390/FOODS12051095

Martínez, J. A., Melgosa, M., Pérez, M. M., Hita, E., & Negueruela, A. I. (2001). Note. Visual and instrumental color evaluation in red wines. *Food Science and Technology International, 7*(5), 439–444. https://doi.org/10.1106/VFAT-5REN-1WK2-5JGQ

Mishra, B. P., Mishra, J., Paital, B., Rath, P. K., Jena, M. K., Reddy, B. V. V., & Pati, P. K. (2023). Properties and physiological e ects of dietary fiber-enriched meat products: A review. *Frontiers in Nutrition, 10*. https://doi.org/10.3389/fnut.2023.1275341

Nieto, G., Fernández-López, J., Pérez-Álvarez, J. A., Peñalver, R., Ros, G., & Viuda-Martos, M. (2021). Valorization of citrus co-products: Recovery of bioactive compounds and application in meat and meat products. *Plants*. https://doi.org/10.3390/plants10061069

Official Journal of the European Union. (2023). *Commission Regulation (EU) 2023/2108 of 6 October 2023 amending Annex II to Regulation (EC) No 1333/2008 of the European Parliament and of the Council and the Annex to Commission Regulation (EU) No 231/2012 as Regards Food Additives Nitrites (E 249–250) and Nitrates (E 251–252)*.

Papuc, C., Goran, G. V., Predescu, C. N., Nicorescu, V., & Stefan, G. (2017). Plant polyphenols as antioxidant and antibacterial agents for shelf-life extension of meat and meat products: Classification, structures, sources, and action mechanisms. *Comprehensive Reviews in Food Science and Food Safety, 16*(6), 1243–1268. https://doi.org/10.1111/1541-4337.12298

Patrón-Vázquez, J., Baas-Dzul, L., Medina-Torres, N., Ayora-Talavera, T., Sánchez-Contreras, Á., García-Cruz, U., & Pacheco, N. (2019). The effect of drying temperature on the phenolic content and functional behavior of flours obtained from lemon wastes. *Agronomy, 9*(9). https://doi.org/10.3390/agronomy9090474

Pérez-Jiménez, J. (2024). Dietary fiber: Still alive. *Food Chemistry, 439*. https://doi.org/10.1016/j.foodchem.2023.138076

Petridis, D., Raizi, P., & Ritzoulis, C. (2014). Influence of citrus fiber, rice bran and collagen on the texture and organoleptic properties of low-fat Frankfurters. *Journal of Food Processing & Preservation, 38*(2014), 1759–1771. https://doi.org/10.1111/jfpp.12139

Powell, M. J., Sebranek, J. G., Prusa, K. J., & Tarté, R. (2019). Evaluation of citrus fiber as a natural replacer of sodium phosphate in alternatively-cured all-pork Bologna sausage. *Meat Science, 157*, Article 107883. https://doi.org/10.1016/j.meatsci.2019.107883

Riel, G., Boulaaba, A., Popp, J., & Klein, G. (2017). Effects of parsley extract powder as an alternative for the direct addition of sodium nitrite in the production of mortadella-type sausages – Impact on microbiological, physicochemical and sensory aspects. *Meat Science, 131*, 166–175. https://doi.org/10.1016/j.meatsci.2017.05.007

Saleem, M., Durani, I., Asari, A., Ahmed, M., Ahmad, M., Yousaf, N., Muddassar, M., & Muddassar, M. (2023). Investigation of antioxidant and antibacterial effects of citrus fruits peels extracts using different extracting agents: Phytochemical analysis with in silico studies. *Heliyon*. https://doi.org/10.1016/j.heliyon.2023.e15433

Sappi Fine Paper North America. (2013). *Defining and Communicating Color: The CIELAB System*.

Shakil, M. H., Trisha, A. T., Rahman, M., Talukdar, S., Kobun, R., Huda, N., & Zzaman, W. (2022). Nitrites in cured meats, health risk issues, alternatives to nitrites: a review. *Foods, 11*(21). https://doi.org/10.3390/foods11213355

Tahmasebi, M., Labbafi, M., Emam-Djomeh, Z., & Yarmand, M. S. (2016). Manufacturing the novel sausages with reduced quantity of meat and fat: The product development, formulation optimization, emulsion stability and textural characterization. *Lwt, 68*, 76–84. https://doi.org/10.1016/j.lwt.2015.12.011

Tayengwa, T., Chikwanha, O. C., Gouws, P., Dugan, M. E. R., Mutsvangwa, T., & Mapiye, C. (2020). Dietary citrus pulp and grape pomace as potential natural preservatives for extending beef shelf life. *Meat Science, 162*, Article 108029. https://doi.org/10.1016/j.meatsci.2019.108029

Tinh, N. T. T., Sitolo, G. C., Yamamoto, Y., & Suzuki, T. (2021). Citrus Limon peel powder reduces intestinal barrier defects and inflammation in a colitic murine experimental model. *Foods, 10*(2), 1–15. https://doi.org/10.3390/foods10020240

Venter, C., Meyer, R. W., Greenhawt, M., Pali-Schöll, I., Nwaru, B., Roduit, C., … O'Mahony, L. (2022). Role of dietary fiber in promoting immune health—An EAACI position paper. *European Journal of Allergy and Clinical Immunology, 77*(11), 3185–3198. https://doi.org/10.1111/all.15430

Viuda-Martos, M., Barber, X., Pérez-Álvarez, J. A., & Fernández-López, J. (2015). Assessment of chemical, physico-chemical, techno-functional and antioxidant properties of fig (Ficus carica L.) powder co-products. *Industrial Crops and Products, 69*, 472–479. https://doi.org/10.1016/j.indcrop.2015.03.005

Viuda-Martos, M., Ruiz-Navajas, Y., Fernández-López, J., & Pérez-Álvarez, J. A. (2010). Effect of added citrus fibre and spice essential oils on quality characteristics and shelf-life of mortadella. *Meat Science, 85*(3), 568–576. https://doi.org/10.1016/j.meatsci.2010.03.007

Xi, W., Lu, J., Qun, J., & Jiao, B. (2017). Characterization of phenolic profile and antioxidant capacity of different fruit part from lemon (Citrus Limon Burm.) cultivars. *Journal of Food Science and Technology, 54*(5), 1108–1118. https://doi.org/10.1007/s13197-017-2544-5

Xi, Y., Sullivan, G. A., Jackson, A. L., Zhou, G. H., & Sebranek, J. G. (2011). Use of natural antimicrobials to improve the control of listeria monocytogenes in a cured cooked meat model system. *Meat Science, 88*(3), 503–511. https://doi.org/10.1016/j.meatsci.2011.01.036

Younis, K., Yousuf, O., Qadri, O. S., Jahan, K., Osama, K., & Islam, R. U. (2022). Incorporation of soluble dietary fiber in comminuted meat products: Special emphasis on changes in textural properties. *Bioactive Carbohydrates and Dietary Fibre, 27*. https://doi.org/10.1016/j.bcdf.2021.100288

Zhang, L., & Piao, X. (2023). Use of aromatic plant-derived essential oils in meat and derived products: Phytochemical compositions, functional properties, and encapsulation. *Food Bioscience, 53*. https://doi.org/10.1016/j.fbio.2023.102520

Zhu, C., Zhang, S., Zhu, N., Wu, Q., Du, M., He, X., Bai, Y., & Wang, S. (2023). Effects of citrus fiber on the emulsifying properties and molecular structure of mutton myofibrillar protein: An underlying mechanisms study. *Food Bioscience, 51*, Article 102304. https://doi.org/10.1016/j.fbio.2022.102304