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Sensory analysis of omelette made from liquid whole egg pasteurised by manothermosonication: unravelling texture and flavour attributes

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ABSTRACT

Manothermosonication (MTS) has been proposed as an alternative to conventional thermal pasteurisation of egg products to enhance food safety and quality. However, its impact on consumer liking and sensory characteristics remains unclear. This study evaluated the effects of MTS on the sensory attributes, texture, and volatile compound profile of omelettes prepared from liquid whole egg (LWE) compared to thermal pasteurisation. Results concluded that MTS-treated omelettes exhibited a firmer texture and higher oxidation levels, leading to distinct metallic and sulphur-like sensory attributes. However, MTS enhanced gel structural properties, suggesting its potential for applications requiring improved gel structure, such as egg tofu surimi products. This study provides novel insights into the impact of MTS on egg product quality, highlighting both its potential benefits and challenges related to oxidation, which should be considered for further investigations.

1. Introduction

There has been an increase in the demand for the development of food products using non-thermal and emerging technologies; this can be due to consumers' interest in sustainable, safer, healthier, fresher, and more nutritious food products (Beitia et al., 2024b; dos Santos Rocha et al., 2022). One of these novel technologies is ultrasound (US), which uses the cavitation phenomenon, a process in which rapid changes in pressure create microbubbles in a liquid, which then collapse violently, releasing energy that drives physical and chemical transformation as its main pathway. However, only limited microbial inactivation can be achieved when the US is applied alone. Manothermosonication (MTS) is an emerging technology that can be used through the combination of US, heating at mild temperatures (40–70 °C), and treatments at elevated pressure (200–500 kPa) (Beitia et al., 2023; López et al., 1994), being considered a promising alternative to conventional thermal pasteurisation treatment of high-acid products like fruit juices (Kahraman et al., 2017; Lee et al., 2013) or low-acid products, like liquid whole egg (LWE) (Beitia et al., 2024a; Mañas et al., 2000). The driving force of MTS is based on the cavitation phenomenon and, as a result of the combined treatments (US, mild temperatures, and elevated pressure), a rapid and violent collapse of the cavitation bubbles is achieved which results in a

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faster microbial inactivation, and at the same time reduces thermal impact. These combined effects might result in a potential protective effect on the food's functional properties (Lorimer and Mason, 1987; Muthukumaran et al., 2006; Raso et al., 1999).

The inactivation potential of MTS in LWE pasteurisation was studied by Beitia et al. (2024a). In that work, 5.0 Log_{10} CFU/mL reductions of *Salmonella* Enteritidis DSM 17420 were found at optimal conditions (277.56 W/cm^2) working under dynamic thermal conditions, providing the same level of food safety as traditional thermal technologies, but requiring a lower heat load. As a result, an improvement in the techno-functional properties of the LWE can be achieved through the application of MTS. Previous work (Beitia et al., 2025) demonstrated that the foaming and emulsifying properties of LWE were improved after MTS compared to thermal and untreated products. Concerning the foaming properties, an increased foam capacity of over 3.2-fold was found compared to thermal-treated LWE, and regarding emulsifying properties higher emulsion stability was achieved due to a smaller droplet size. Such foaming capability may have relevance in the baking industry, while the emulsifying capacity has an interest in the production of products where eggs are used as an emulsifying ingredient, such as in mayonnaise (Jun et al., 2020; Li-Chan et al., 2013). Nevertheless, enhanced food properties may also result from applying MTS in LWE, like the generation of a more elastic gel after product coagulation (Beitia et al., 2025). Such properties may be useful in manufacturing food gels where egg, especially egg white (EW), is used as a gelling ingredient (e.g., egg tofu or surimi products). Traditional EW gelation is insufficient for such products (Wei and Jie, 2011); hence it is common practice to use additives (e.g., xanthan gum or phosphates) to maximise gelation (Jin et al., 2021; Salek et al., 2015; Zhang et al., 2019).

Sensory and consumer science is essential in developing and evaluating new products and technologies, as they help identify key sensory attributes that drive consumer preferences (Varela and Ares, 2012). Methods such as sensory profiling with trained panels and consumer-based approaches like Check-All-That-Apply (CATA) and Rate-All-That-Apply (RATA) allow for a more comprehensive description of sensory characteristics. Both techniques can be performed with trained or consumer panels using a predetermined list of attributes that describe a particular product. For the CATA analysis, consumers only select the attributes present in the product. On the other hand, on RATA, consumers select the attributes present in the product, and then rate the selected terms based on their intensity or applicability (Ares et al., 2014). Therefore, the RATA method offers a direct measurement of the intensity of the perceived sensory attributes, with potential discrimination between products that have similar sensory profile attributes while varying in the intensity of those features (Baião et al., 2022). Special attention has been given to the RATA method for its ability to capture both the presence and intensity of sensory attributes, providing improved discrimination among similar products (Giacalone and Hedelund, 2016). Recent studies highlighted the importance of using consumer-based sensory methodologies to assess novel food processing technologies, as consumer perception plays a critical role in market acceptance (Silva et al., 2024).

Cooked eggs have been characterized by flavour attributes such as fresh scrambled egg, sulphury, sweet, and dairy, linked to lipid-derived compounds (e.g., aldehydes), sulphides, and Maillard-derived compounds (e.g., pyrazines) (Warren et al., 1995). Since these compounds are influenced by the presence of precursors and processing conditions, it is important to consider them, together with the resulting sensory flavour profile and any subsequent influence on consumer acceptance. Omelette represents a commonly consumed cooked egg product worldwide, which can be prepared uniformly (Davidson, 2014). Previous studies on omelettes, have explored sensory attributes of alternative omelette formulations, highlighting differences in texture and consumer perception compared to conventional egg-based products (Zhou et al., 2023; Baxter et al., 2024). Additionally, Chauhan and Sharma (2003) and Ekpo et al. (2024) assessed overall sensory dimensions, including colour, appearance, flavour, texture, tenderness, taste, overall acceptability, and desirability. Those studies have typically focused on broad sensory dimensions without detailing specific attributes within each category. Sensory dimensions (e.g., appearance, odour, texture, and taste) serve as overarching categories to organise perceptions, while specific sensory attributes (e.g., egg flavour, saltiness, metallic taste) represent measurable and detailed characteristics within these dimensions. The RATA method allows for a more precise evaluation of how new processing technologies might influence the sensory perception of omelettes, providing deeper insights beyond general sensory assessments.

In this study, the LWE is processed by using an emerging processing technology, so it is important to evaluate it against the traditional method (thermal pasteurisation), and optimally also under industrially relevant conditions. Thus, this work aims to evaluate MTS as an alternative to thermal processing, with the primary comparison focusing on its effects on texture, colour, and sensory perception. The analysis considers both LWE and the resulting omelettes, where thermal samples serve as reference point to assess the impact of MTS. Colour, lipid oxidation, and texture were evaluated in both matrices (LWE and omelettes), while sensory profiling and overall liking of omelettes were assessed using a consumer panel.

2. Material and methods

2.1. Sample preparation

Fresh unpasteurised LWE was obtained from OVOBEST Eiprodukte GmbH & Co. KG (Neuenkirchen-Vörden, Germany) and subjected to respective pasteurisation treatments (see 2.1.1). Additionally, a commercial thermally pasteurised LWE from the same company was kindly provided and used as a control for the tests performed in this study. The pasteurised LWE was prepared as an omelette for the sensory evaluation. LWE (400 mL) and salt (2 g) were mixed with a hand mixer, then poured into a 10 × 10 cm tray and cooked in a steam oven preheated at 100 °C for 4 min. The resulting omelette was divided into 10 squared pieces.

2.2. Pasteurisation treatments

2.2.1. Manothermosonication

The pilot scale MTS equipment described in Beitia et al. (2024a) was used to apply treatments. The equipment had three main components (i) US-probe system (UPI2000, Hielscher, Berlin, Germany) with an 18 mm tip-diameter sonotrode (BS2d18, Hielscher, Berlin, Germany), which operated at 20 kHz (constant frequency) and used a probe depth of 1.20 cm; (ii) water bath (DIL e.V., Quakenbrück, Germany) working as a temperature control system by the circulation of hot water through the US chamber (closed double jacket cell with 170 mL of capacity); (iii) valve to increase the pressure in the chamber. Treatments at 277.56 W/cm^2 of US intensity (UI) (i.e., wave amplitude of 132 μm and pressure of 300 kPa) were applied under dynamic thermal conditions, as previously reported as optimal for achieving a 5.0 Log_{10} CFU/mL reduction of *S.* Enteritidis DSM 17420 in LWE (Beitia et al., 2024a). Moreover, such conditions were previously found to improve the LWE functional protein properties compared with thermal pasteurisation (Beitia et al., 2025). Treatments were applied semi-continuously by recirculating 500 mL of LWE (initial temperature 40 °C) through the processing chamber (30 s retention time) until a final temperature of 57 °C was reached (3.5 min treatment time), followed by cooling on ice.

2.2.2. Thermal treatment (TT)

The traditional TT was applied following established guidelines for the thermal pasteurisation of LWE, aiming to achieve a 5.0 Log_{10} CFU/mL reduction of *Salmonella* spp., as recommended by Froning et al. (2002) and USDA-FSIS (2017). While no direct enumeration of *Salmonella* spp. was performed in this study, the applied time-temperature combination (60 °C for 3.5 min) is widely accepted in the literature as effective for ensuring microbial safety in egg products. For that, two water baths (DIL e.V., Quakenbrück, Germany) were employed to conduct the process: the first (90 °C) to heat 500 mL LWE to 60 °C (dynamic thermal profile) and the second (62.5 °C) to hold the product temperature at 60 °C for 2.93 min (isothermal profile) to achieve the target microbial inactivation, before finally cooling the samples on ice (Beitia et al. 2025).

2.3. Sensory analysis

A panel of eighty consumers was recruited from the Osnabrück University consumer database to evaluate the samples. They were all regular consumers of eggs, 68 % followed an omnivorous diet, while 32 % followed a flexitarian diet, 51 % were female, 49 % male, and the average age was 48 ± 19 years old. Sensory evaluation was carried out in individual tasting booths, with the room complying with sensory specification ISO 8589:2007. The study was approved by the Ethical Committee of the Faculty of Sciences, University of Porto, Portugal (authorisation number CE2023/P64). Complete confidentiality guaranteed adherence to the Helsinki protocol and informed consent was confirmed by the participants at the beginning of the study. After following the protocol for the omelette preparation described in Section 2.1, samples were placed on a white porcelain plate and blind-labelled with three-digit random codes. The control sample was presented in duplicate within the sample set (both blind coded) to assess the tasters' ability to perform the task, discriminate between samples and replicate their results (Hopfer and Heymann, 2013). During the session, to compensate for eventual carry-over effects, each panellist received a set of four samples following a sequential monadic presentation, with a balanced presentation order (MacFie et al., 1989). Panellists were given a glass of water and unsalted crackers and instructed to rinse their palate between samples.

2.3.1. Overall liking

The overall liking of the omelette samples was evaluated using the classic 9-point hedonic scale, ranging from 1 - "dislike extremely" to 9 - "like extremely" (Peryam and Pilgrim, 1957). To minimise the bias that analytical thinking can have upon hedonic responses, sensory attributes were assessed (using the RATA methodology outlined below) after the evaluation overall (King, Meiselman, and Carr, 2013).

2.3.2. Sensory profile, Rate-All-That-Apply (RATA)

2.3.2.1. Development of the RATA ballot. The RATA ballot was developed by incorporating terms from previously published consumer studies on sensory evaluation of omelettes, which were then refined through group discussions and a pilot tasting session. To ensure the applicability and clarity of the attributes, a pilot test with eight untrained consumers was conducted. Participants were asked to confirm their understanding of the terms and describe them in their own words, following the approach of Baião et al. (2021). The final ballot of 17 sensory attributes shown in Table 1 was obtained, with attributes organised in four dimensions to reduce the cognitive effort required by the participants: appearance (4), odour (3), texture (6) and taste (4) (Ares et al., 2014).

2.3.2.2. RATA evaluation. The consumers were asked to perform a RATA evaluation with the previously defined list (Table 1). While fixing the order of the sensory dimensions, individual attributes within each sensory dimension were presented in a randomised order of presentation, different for each participant and the same within each participant (Meyners & Castura., 2016a). Consumers were asked to check the terms they considered applicable for describing samples and then to rate the intensity of each selected attribute using a 5-point structured scale (from 1 = "slightly applicable" to 5 = "extremely applicable") (Ares et al., 2014; Meyners et al., 2016b). The consumers who participated in the evaluation had no prior training. However, before assessing the first sample, the test procedure was explained to them, instructing them to identify the presence or absence of the listed attributes and rate their intensity when applicable. To aid understanding, an example using a product different from the test samples was provided (Ares et al., 2014).

Table 1
List of 17 attributes divided into four dimensions (translated into German). All attributes were rated as absent or present and, if present, rated using a 5-point structured scale (from 1 = "slightly applicable" to 5 = "extremely applicable").

Sensory dimension	Sensory attributes
Appearance	Pale colour (Helle Farbe), Yellow colour (Gelbe Farbe), Greyish colour (Gräuliche Farbe), Greenish tonalites (Güne Färbung)
Odour	Egg-like (Ei-typisch), Metallic (Metallisch), Sulphur-like (Schwefelähnlich)
Texture	Dense (Dicht), Silky/Smooth (Seidig), Soft (Weich), Crispy (Knusprig), Ruberry/Gummy (Zäh/gummiartig), Airy/Porous (Luftig)
Taste	Egg-like (Ei-typisch), Salty (Salzig), Metallic (Metallisch), Aftertaste (Nachgeschmack)

2.4. Colour analysis

Colour measurements were conducted on the LWE samples (before sample preparation) after pasteurisation treatments (MTS and TT) and on the LWE commercial sample (control). Similarly, measurements were performed in the respective omelette samples in three different locations (top, centre, and bottom parts). Colour coordinates (L^*, a^*, b^*) were obtained with Spectrophotometer CM-600d (Konica Minolta, Chiyoda, Japan) using as a light source the illuminant D_{65} for the measurement of the values of lightness (L^*), red/green hue (a^*), and yellow/blue hue (b^*). Moreover, from those coordinates, the Hunter whiteness (W^*) of the samples was calculated using Eq. (1). Measurements were done at room temperature (20 °C).

$$W^* = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \quad (1)$$

2.5. Analysis of lipid oxidation and volatile compounds

2.5.1. Spectrophotometric evaluation of lipid oxidation

Lipid oxidation was assessed by using the thiobarbituric acid-reactive substances (TBARS) method, as described by Ribeiro et al. (2023a). This spectrophotometric method quantifies secondary lipid oxidation products, primarily malondialdehyde, which reacts with 2-thiobarbituric acid (TBA) to form a red-pink pigment measurable at 538 nm. Briefly, 2 g of each sample (MTS, TT, and untreated LWE) was mixed with a 2 mL of a 7.5 % trichloroacetic acid (TCA; AppliChem, Darmstadt, Germany) solution and centrifuged at 4000 rpm for 30 min at 4 °C (Megafuge 16, Thermo Scientific, Waltham, USA). Then, 1 mL of the resulting supernatant was mixed with 1 mL of a 20 mM TBA (Sigma-Aldrich, San Luis, USA) solution in 99 % glacial acetic acid (Sigma-Aldrich, San Luis, USA). The resultant solutions were subsequently immersed in a water bath at 90 °C for 40 min before cooling on ice for 10 min. Finally, the absorbance of the solutions was measured with a Microplate reader (CLARIOstar Plus, BMG Labtech, Ortenberg, Germany) against a reagent blank, using 1,1,3,3-tetramethoxypropane (Fluorochem, Hadfield, UK) in the range of 0.2 - 1.0 μM to obtain the malondialdehyde standard curve. Results were expressed as μg TBARS/g of LWE.

2.5.2. Identification of volatile compounds

Identification and semi-quantitation of volatile organic compounds (VOCs) in treated (MTS and TT) compared to untreated LWE samples was conducted using headspace-solid phase microextraction (HS-SPME) followed by gas chromatography-mass spectrometry (GC–MS) detection, as described by Ribeiro et al. (2023c). The focus on analysing LWE instead of omelettes was intentional to evaluate the direct impact of the pasteurisation treatments on the volatile profile of the base ingredient, minimising potential confounding effects from the cooking process or matrix interactions during omelette preparation. This approach allowed a more accurate assessment of treatment-induced changes in volatile compounds.

The procedure involved adding 2 g of LWE sample, 4 g of sodium chloride (Sigma-Aldrich, Burlington, USA), and 2 mL of distilled water to a 15 mL glass headspace vial. The vial was capped and incubated at 40 °C for 5 min at 100 rpm. Afterwards, VOCs were extracted at 40 °C for 30 min at 100 rpm, using a 50/30 μm Divinylbenzene/Carboxen/Polydimethylsiloxane 2 cm StableFlex™ fiber (Sigma-Aldrich, Burlington, USA), preconditioned at 250 °C for 5 min in the GC injector. VOCs were desorbed thermally in the injection port of the gas chromatograph-mass spectrometer (GCMS-QP2010 Ultra, Shimadzu Corporation, Kyoto) and operated in splitless mode at 250 °C for 5 min.

Subsequently, VOCs were separated using a DB-5MS capillary column (30 m × 0.25 mm, d.f. 0.25 μm; Agilent Technologies, Santa Clara, USA) with high-purity helium as the carrier gas at a constant linear velocity of 36 cm/s. The temperature programming for the GC–MS method was selected to optimise the separation of a wide range of volatile compounds, particularly lipid oxidation products. The temperature conditions were isothermal at 40 °C for 5 min, followed by a ramp to 180 °C at 8 °C/min to separate low-boiling compounds. The subsequent ramp to 250 °C at 30 °C/min was chosen to reduce analysis time while ensuring the elution of higher-boiling compounds. The final hold at 250 °C for 5 min ensured complete elution of all volatiles of interest without compromising resolution. Mass spectra were recorded over the m/z range of 45–350, with a scan time of 0.3 s. The MS transfer line and ion source temperatures were set at 250 °C and 230 °C, respectively. VOCs were identified by comparing the MS fragmentation patterns with those in the NIST 2.0 Mass-Spectral library (National Institute of Standards and Technology, Gaithersburg, USA) and using n-alkanes-based retention indices found in the literature. Semi-quantification of VOCs was conducted by peak area normalisation, expressed as relative abundance (%). Data processing and VOC identification and semi-quantification were performed using AMDIS (ver. 2.72) and NIST MS Search software (ver. 2.2, National Institute of Standards and Technology, Gaithersburg, USA).

2.6. Texture characterisation

Textural properties of the omelettes made from the MTS, TT, and the commercial (control) LWE samples were subjected to two textural analysis methods (compression strength test and cutting strength test) using a TA-XT2 texture analyser (Stable Micro Systems, Godalming, UK). Measurements were performed at room temperature (20 °C) and with a load on the trigger point of 5.10 g.

2.6.1. Compression strength test

Tests were performed on the top surface of the omelette pieces using a 20 mm-diameter cylindrical metal probe with a compression distance (gap) of 5 mm and pre-test, test, and post-test speeds of 1.0, 0.5, and 1.0 mm/s. Compression force was determined from the force-distance curves.

2.6.2. Cutting strength test

Blocks of 14 mm-height and 20 mm-width were prepared from the omelette samples and a cutting blade probe (blade inner part of 30 mm) was used for the test. A cutting distance (gap) of 20 mm and pre-test, test, and post-test speeds of 1, 2, and 10 mm/s were selected, respectively. Maximum cutting force was determined from the force-distance curves.

2.7. Statistical analysis

2.7.1. Physico-chemical analysis

For the physico-chemical analysis of the LWE (colour and fat oxidation) and of the omelette (colour and texture) samples, SigmaPlot 13.0 Statistical Analysis Software (Systat Software, Inc., San Jose, California, USA) was used. Values are presented as the averages and standard deviation (SD) of three independent biological replicates using three technical replicates in the case of fat oxidation, and three technical measurements from three different points in each biological replicate in the case of colour and texture analysis. For the sample comparison, the significant differences at $p < 0.05$ were obtained by one-way analysis of variance (ANOVA) after confirming the non-departure of the data from a normal distribution, following the Shapiro-Wilk's normality test (data not shown). Moreover, MATLAB Version R2021b (The MathWorks, MA, USA) was used to obtain graphical illustrations.

2.7.2. Overall liking

Due to their non-parametric distribution, sensory profiling and overall liking data were analysed using the Friedman test. When needed, a post hoc test with multiple pairwise comparisons was run using the Wilcoxon procedure to determine the differences between samples ($p <$ 0.05). Statistical analyses were performed using XLSTAT® software (version 2021.2.1, Addinsoft, New York).

2.7.3. Sensory profile

For the analysis of the RATA data, the recommendations of Ares et al. (2014) and Meyners et al. (2016b) were followed. Scores were calculated for each case by summing the scores provided by the consumers who selected that term as applicable for describing a respective sample. Correspondence Analysis (CA) was performed, considering Chi-square distances (Meyners et al., 2013) on the sum of scores given by all consumers to each term, i.e., RATA scoring (Ares et al., 2014). With this analysis, a sensory map of the samples was obtained. Based on the CA results, a multi-dimensional alignment (MDA) approach (Meyners et al., 2013) was used to assess attribute-sample correlation. The inverted horizontal scale aids its interpretation: values to the right of 90° indicate positive correlation, while those to the left indicate negative correlation, with significance thresholds at 45° and 135°

To convert RATA data to Check-All-That-Apply (CATA) data, the responses were collapsed into two levels – the value 0 (attribute not selected) or the value 1 (attribute selected). The resulting CATA dataset was analysed using the CATA analysis tool in XLSTAT version 2021.2 (Addinsoft, Paris, France), which uses Cochran's Q statistic for comparison of the binary data (Cochran, 1950). A penalty-lift analysis (PA) was used to investigate the extent of change to overall liking scores, whenever sensory attributes were considered present of absent, with significance set at $p < 0.05$ (Ares et al., 2014).

2.8. Multiple factor analysis (MFA)

MFA was applied to assess the consensus between all the analysed variables data sets: colour parameters, texture measurements, lipid oxidation, volatile profile, sensory profiling, and overall linking, to understand the relationships between these variables and their relationship with the products (Louw et al., 2013).

3. Results and discussion

3.1. Sensory analysis

3.1.1. Overall liking

The results (Table 2) showed significant differences between overall liking means scores from the MTS and the TT samples ($p < 0.05$). The TT sample had a higher mean overall liking score (5.8 ± 1.5) than both control samples (5.4 ± 1.5), and all three of these samples had a higher

Table 2
Overall liking and RATA sensory attributes of LWE commercial (control 1 and control 2), TT, and MTS omelette samples.

	Control 1	Control 2	TT	MTS	*p*-value
Overall liking *	5.4 ± 0.2 ^{b}	5.4 ± 0.2 ^{b}	5.8 ± 0.2 ^{a}	5.0 ± 0.2 ^{c}	0.012
A_Light_colour	4.1 ± 0.1 ^{a}	3.6 ± 0.1 ^{b}	3.0 ± 0.1 ^{c}	2.7 ± 0.1 ^{c}	<0.0001
A_Yellow_colour	2.5 ± 0.2 ^{c}	2.6 ± 0.2 ^{c}	3.7 ± 0.1 ^{a}	3.5 ± 0.1 ^{b}	<0.0001
A_Greyish_colour	0.5 ± 0.1 ^{a}	0.5 ± 0.1 ^{a}	0.1 ± 0.0 ^{b}	0.2 ± 0.1 ^{b}	<0.0001
A_Green_colour	0.2 ± 0.0 ^{ab}	0.2 ± 0.1 ^{a}	0.1 ± 0.0 ^{ab}	0.1 ± 0.0 ^{b}	0.033
O_Egg_odour	2.9 ± 0.2 ^{a}	2.9 ± 0.2 ^{a}	3.1 ± 0.2 ^{a}	2.6 ± 0.2 ^{a}	0.055
O_Metallic	0.4 ± 0.1 ^{b}	0.6 ± 0.1 ^{b}	0.5 ± 0.1 ^{b}	1.0 ± 0.2 ^{a}	0.007
O_Sulphur-like	0.8 ± 0.1 ^{b}	0.8 ± 0.1 ^{b}	0.7 ± 0.1 ^{b}	1.2 ± 0.2 ^{a}	<0.001
Tx_Dense	3.0 ± 0.1 ^{c}	3.1 ± 0.1 ^{bc}	3.4 ± 0.1 ^{a}	3.3 ± 0.2 ^{ab}	0.002
Tx_Silky	1.4 ± 0.1 ^{a}	1.6 ± 0.2 ^{a}	1.5 ± 0.1 ^{a}	1.4 ± 0.1 ^{a}	0.751
Tx_Soft	2.6 ± 0.1 ^{a}	2.7 ± 0.1 ^{a}	2.5 ± 0.1 ^{a}	2.5 ± 0.1 ^{a}	0.524
Tx_Crispy	0.2 ± 0.1 ^{a}	0.2 ± 0.1 ^{a}	0.2 ± 0.1 ^{a}	0.1 ± 0.0 ^{a}	0.353
Tx_Tough/ rubbery	1.4 ± 0.2 ^{a}	1.4 ± 0.2 ^{a}	1.4 ± 0.2 ^{a}	1.6 ± 0.2 ^{a}	0.726
Tx_Airy	2.3 ± 0.2 ^{a}	2.1 ± 0.2 ^{a}	1.9 ± 0.2 ^{b}	1.6 ± 0.1 ^{b}	0.000
T_Egg_flavour	2.9 ± 0.1 ^{a}	3.1 ± 0.1 ^{a}	3.0 ± 0.1 ^{a}	2.6 ± 0.2 ^{a}	0.122
T_Salty	1.3 ± 0.1 ^{a}	1.3 ± 0.1 ^{a}	1.2 ± 0.1 ^{a}	1.1 ± 0.1 ^{a}	0.238
T_Metallic	0.5 ± 0.1 ^{b}	0.5 ± 0.1 ^{b}	0.4 ± 0.1 ^{b}	1.1 ± 0.2 ^{a}	<0.0001
T_Aftertaste	1.2 ± 0.1 ^{ab}	1.3 ± 0.1 ^{a}	0.9 ± 0.1 ^{b}	1.5 ± 0.2 ^{a}	0.010

Values are presented as mean (± standard error, SE), $n = 80$. Different letters in the same row indicate a significant difference according to the Friedman test with Wilcoxon post-hoc comparison analysis ($p < 0.05$).
* Evaluated on a 9-point hedonic scale, ranging from 1 – "dislike extremely" to 9 – "like extremely" (Peryam and Pilgrim, 1957). The 17 sensory attributes were evaluated on a scale from 1 to 5, with 1 = "slightly applicable" to 5 = "extremely applicable", if considered applicable. Sensory attributes ordered by sensory dimension: A – appearance, O – odour, Tx – texture and T – taste).

overall liking score than the MTS sample (5.0 ± 1.8). None of the products achieved a high mean overall liking score (above 7), being scored mainly between "neither like nor dislike" to "like slightly". A previous study of omelettes produced by LWE also reported mean overall liking scores between 5 and 7, on a 9-point hedonic scale (Espina et al., 2014).

3.1.2. Sensory profile

Table 2 summarises the results from the RATA analyses. From the 17 sensory terms used in this study, nine showed significant differences ($p < 0.05$), all the appearance terms (light colour, yellow colour, greyish colour, and green colour), metallic and sulphur-like odours, airy and dense texture, and metallic taste and aftertaste. Visually, the consumer perceived the control samples to be significantly lighter, less yellow, and greyer than the experimental samples (TT and MTS). However, the different pasteurisation treatments (TT and MTS) did not lead to differences in the perceived colour of the omelettes.

The eggy odour and flavour and the salty taste did not differ between the omelette samples. However, the MTS-egg omelette scored significantly higher than both the TT and control samples in sulphur odour, metallic odour and metallic tastes, and higher aftertaste than the TT sample. Descriptive sensory evaluation studies involving eggs have predominantly focused on cooked forms, such as boiled eggs, rather than on raw or minimally processed egg products. Additionally, studies investigating the effects of thermosonication (TS) and US have primarily been conducted on food products other than eggs. For instance, Walkling-Ribeiro et al. (2009) studied the use of TS with pulsed electric field (PEF) in comparison to the high-temperature short time (HTST) methodology in orange juices and also found a metallic flavour in TS/PEF treated orange juice (10.8 % vs. 5.4 %; $p < 0.05$). The work by Marchesini et al. (2012; 2015) showed that metallic flavour is correlated with the duration of the US treatment, where increasing the sonication time led to greater production of off-flavours, especially metallic, burnt, rubbery and sharp flavours, leading to a rejection of the milk samples analysed.

Similarly, previous studies have shown that US treatment of milk before yogurt production significantly improved the textural properties of the final product, yet increased the formation of oxidation-related compounds, which contributed to off-flavours (Carrillo-Lopez et al., 2021). The sulphur-like flavour may come from hydrogen sulphide (H_2S), which can be formed when eggs become less acidic due to protein denaturation and interactions between sulphur-containing amino acids (Abrahamsen and Narvhus, 2022; Mercer, 2020). The sulphur-containing volatiles that contribute to the overall flavour of foods can be produced during processing. Tinkler and Soar (1920) found that H_2S was produced when eggs were hard-boiled (Chen and Chen, 1984). Beitia et al. (2025) showed that the pH of the MTS treatment (8.07 ± 0.01) and the TT treatment (8.05 ± 0.01) were slightly higher than the pH of the untreated sample (7.94 ± 0.05) ($p < 0.05$). In this work, the MTS sample presented a characteristic sulphur-like flavour. Furthermore, of the six texture attributes evaluated by the consumers, only two differed significantly between the samples. The control samples were significantly more "airy" structure than the TT and MTS samples and predominantly less dense. The type of pasteurisation (TT compared to MTS) did not affect the sensorial texture.

Fig. 1 shows the configuration of the samples in the first and second dimensions of the CA applied to the RATA data of omelettes, which explained 97.3 % of the total variance of the experimental data. The representation shows that the consumers discriminated between the omelette samples that had been processed under different conditions. There was a clear separation between the control, TT, and MTS samples. The MTS samples were situated furthest from overall liking (Fig. 1). In our study, the MTS sample was characterised by a metallic odour and taste; both metallic aspects of the MTS samples correlated to their higher levels of oxidation (as described in Section 3.3), which was related to lower consumer liking.

The RATA approach allows the measurement of attributes' intensity to improve sample description and discrimination, which was a limitation of the CATA approach due to its binary nature, as it does not capture intensity variations (Ng et al., 2013). Fig. 1 shows a clear separation between samples, with most of the attributes correlated with the control samples. However, the RATA data can be transformed into CATA data when collapsed into two levels (selected / not selected), independent of their intensity. When analysed as CATA data, it is possible to identify the impact of the attributes on overall liking through a penalty analysis (PA). Fig. 2 uses the "+" and "-" signals to demonstrate which attributes had positive or negative impacts on liking ($p < 0.05$). It was found that both egg flavour and dense texture had a positive lift (the overall liking increased when the attribute was present). In contrast, metallic taste, greyish colour, and aftertaste had a negative penalty, i.e., the overall liking decreased when the attribute was present. When comparing the data from the MDA with the PA, it can be seen that the egg flavour has a positive impact and was positively correlated with both commercial samples.

3.2. Colour analysis

The colour characterisation of the product before cooking (LWE; Table S.1, see Supplementary) and after cooking (omelette; Table 3) was

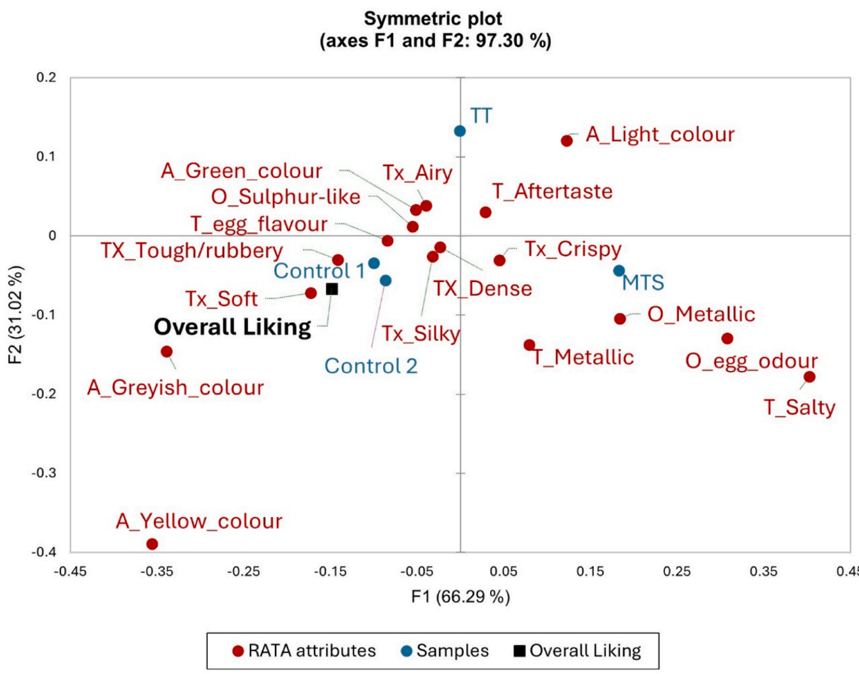

Fig. 1. Biplots with dimensions 1 and 2 of CA of RATA data from the sensory profiling of omelettes. The CA was performed on the sum of scores given by all consumers to each term to describe each sample (RATA scoring). Sensory attributes ordered by sensory dimension: A – appearance, O – odour, Tx – texture, and T – taste).

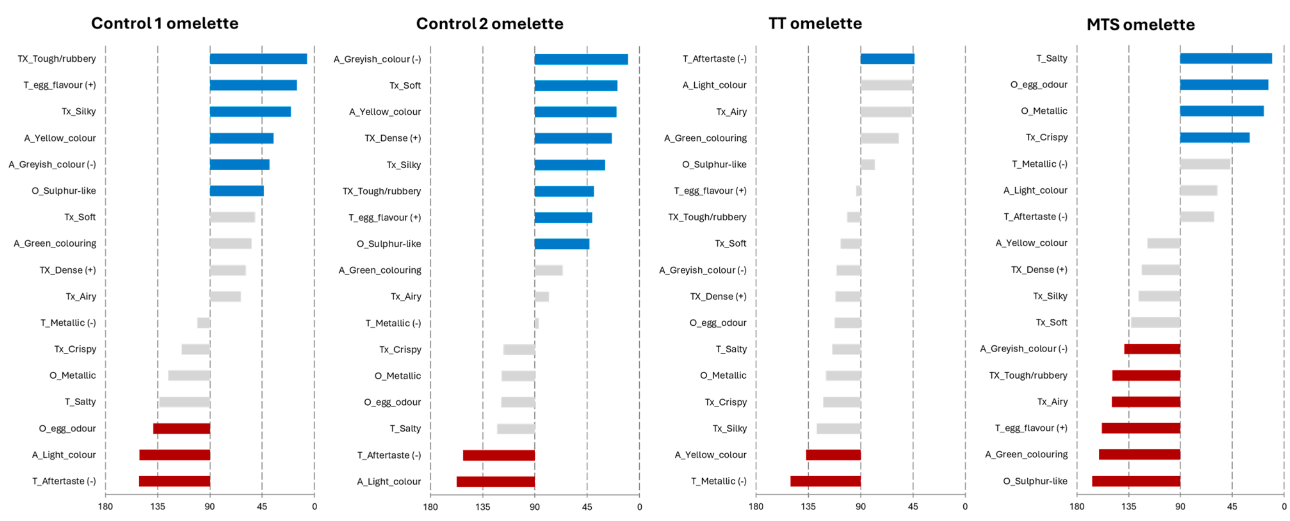

Fig. 2. Correlation between omelette attributes and products based on the vectorial angle (0 to 180°) between samples and attributes, based on the MDA. The MDA was performed using data from de CA on the sum of scores given by sensory test participants to each term for describing the omelette samples. Attributes represented with symbols (+) or (-), were identified as having a significant impact on the overall liking through a Penalty/Lift Analysis. Sensory attributes grouped by sensory dimension: A – appearance, O – odour, Tx – texture and T – taste).

assessed by using the whiteness (W^*) parameter. In addition, a full description of the colour coordinates (L^*, a^*, b^*) obtained in both products can be found in Table S.2 (see Supplementary). Firstly, significant differences ($p < 0.05$) were found between the three samples, exhibiting the highest whiteness value of 57.34 ± 0.03 in the control LWE and the lowest whiteness value of 49.18 ± 0.62 in the TT LWE. As both samples were thermally treated, the low value found in the TT sample might have resulted from the way how the heat treatment was conducted (batch processing). Consequently, compounds responsible for the colour attributes, such as carotenoids in egg yolk (EY) (Bi et al., 2020; Chen et al., 1995) may be more affected by batch processing leading to a darker product. Concerning the MTS sample, a whiteness value of 54.18 ± 1.44 was obtained, being closer to the commercial LWE, but still significantly lower. As MTS was applied in a semi-continuous mode, the sonication treatment may have influenced the colour compounds in the LWE in a manner comparable to the effects observed from continuous thermal processing, as in the commercial sample. Nevertheless, no significant differences ($p < 0.05$) were found in colour results in the omelette parts investigated (top, centre, bottom) from the three LWE pasteurisation treatments. Only the whiteness in the centre part of the omelette in the TT sample (68.16 ± 0.36) was significantly lower than the commercial and MTS samples (70.65 ± 0.46 and 71.24 ± 0.80, respectively). Thermal processing has been shown to influence EY colour due to heat-induced oxidation and changes in

Table 3
Effect of MTS and TT on the colour and textural properties of omelettes made with the respective treated LWE compared to an omelette made with a commercial thermally pasteurised (control) sample. The shown data represent the mean values of three independent biological replicates and the SD.

	Control	TT	MTS
Colour analysis, Hunter whiteness (W^*)			
- Top part	48.44 ± 1.77 [a]	48.23 ± 2.59 [a]	51.10 ± 2.83 [a]
- Centre part	70.65 ± 0.46 [a]	68.16 ± 0.36 [b]	71.24 ± 0.80 [a]
- Bottom part	66.71 ± 1.75 [a]	64.19 ± 1.08 [a]	65.73 ± 1.93 [a]
Texture analysis			
- Compression strength, kPa	29.99 ± 2.12 [b]	26.54 ± 2.58 [b]	43.07 ± 5.68 [a]
- Cutting strength, kPa	5.22 ± 0.56 [b]	4.22 ± 1.16 [b]	8.67 ± 0.84 [a]

Different letters in the same row indicate a significant difference ($p < 0.05$).

pigment stability, which vary depending on processing conditions, such as temperature and time (Bi et al., 2020). Therefore, changes in colour in the current study are unlikely to have affected consumer liking because the extent of difference due to MTS was small, whereas where the whiteness of the cooked egg product increases this can negatively impact acceptability, as demonstrated where additives such as xanthan gum (0.06 % w/w) were used in EW gels (Zhang et al., 2019). Moreover, sensory results were partly in line with the instrumental colour results, in that the control sample was whiter than the TT sample, although the instrumental measurements were not found to be whiter than the MTS-egg omelette.

3.3. Lipid oxidation and volatile compounds

Results from the oxidation analysis (Table S.1, see Supplementary) revealed that the presence of secondary lipid oxidation compounds after MTS (0.93 ± 0.04 μg TBARS/g) was significantly higher ($p < 0.05$) than in the control (untreated) and TT LWE, whose fat oxidation values (0.53 ± 0.01 and 0.58 ± 0.04 μg TBARS/g, respectively) were comparable to those found in the other egg studies (de Souza and Fernández, 2011; Faitarone et al., 2016; Kralik et al., 2021; Ribeiro et al., 2023b). The higher lipid oxidation resulting from the MTS treatment of the LWE, which is linked with the metallic taste found in the sensory analysis (see Section 3.1.2) might likely have resulted from the cavitation and its sonochemical effects. The basis of this phenomenon is the propagation of acoustic waves through a liquid food product at continuous cycles of microbubble creation and implosion. This situation results in the release of large amounts of energy and localised mechanical, thermal, and sonochemical effects, such as the formation of highly reactive free radical species of hydroxyl radical ($OH^\bullet$) and hydrogen atoms ($H^\bullet$) from water molecule fragmentation (H_2O), a phenomenon called sonolysis, which can react with lipid components of the LWE. Moreover, the generation of hydrogen peroxide (H_2O_2) from the $OH^\bullet$ species may also occur from the cavitation phenomenon (Beitia et al., 2023; Gogate and Kabadi, 2009; Hua and Thompson, 2000; Zupanc et al., 2019). Subsequently, these triggered chemical species might influence the lipid oxidation of the LWE compounds, like phospholipids, fatty acids (Liang et al., 2020a), or low-density lipoprotein (LDL) cholesterol found in the EY part (de Souza and Fernández, 2011). The MTS egg omelette had a significantly higher metallic odour and taste compared to the TT and control products, and this may likely have resulted from the greater extent of lipid oxidation in the MTS egg. Similar sensory defects have been observed in ultrasound-treated dairy products, where prolonged sonication resulted in off-flavours described as metallic, burnt, and rubbery (Marchesini et al., 2012; 2015). Moreover, sulphur-containing compounds, such as H_2S, which are naturally formed in eggs due to amino acid degradation, may have increased by the cavitation effects of MTS, leading to a sulphur-based off-flavour. This effect has been observed in thermally processed eggs, where increased pH levels and heating conditions promote the sulphur compound formation (Chen and Chen, 1984; Mercer, 2020).

The VOC headspace profiles of the treated (MTS and TT) and untreated LWE samples were detected by GC–MS. Table S.3 (see Supplementary) summarises the volatile substances detected across all samples, along with their relative abundance. Notably, distinct compounds were identified in the MTS and TT LWE samples, as presented in Table 4. From the volatile compounds identified in the MTS LWE sample, four compounds, 3-methyl-1-butanol (0.38 ± 0.15 %), 2-heptanone (0.44 ± 0.10 %), benzaldehyde (2.26 ± 0.28 %), and 1-heptanol (0.22 ± 0.02 %), were linked to oxidative flavour, collectively comprising 3.30 % of the sample's volatile profile, as documented in the scientific literature (Cardenia et al., 2015; Gao et al., 2023; Liang et al., 2020b; Wang et al., 2023; Yu et al., 2023). In contrast, the TT LWE sample contained oxidative descriptors such as 1-penten-3-ol (0.38 ± 0.13 %), pentanal (0.78 ± 0.41 %), and 3,5-octadien-2-one (0.68 ± 0.14 %), which constituted 1.84 % of the total volatile compounds, in alignment with literature on oxidative off-flavours (Cardenia et al., 2015; Liang et al., 2020b; Wang et al., 2023; Zheng et al., 2022). Additionally, some volatile compounds were present in both treated LWE samples, as shown in Table S.4 (see Supplementary), but these descriptors were not associated with oxidative contributions in the LWE samples.

Regarding the contribution of individual compounds to the oxidative flavour in the samples, the TT LWE contained substances typically associated with classical oxidation markers, such as pentanal (an aldehyde) and 1-penten-3-ol (an unsaturated alcohol), both of which are products of thermal processing (Eymard et al., 2009). These compounds generally originate from the oxidation of fatty acids found predominantly in EY, contributing to off-flavours such as rancid, stale, or grassy notes in egg products (Cardenia et al., 2015; Liang et al., 2020b; Wang et al., 2023; Zheng et al., 2022). However, the MTS LWE exhibited a higher concentration of oxidative flavour compounds compared to the TT samples, potentially leading to a synergistic interaction among these compounds, despite them not being the classical oxidation markers. Notably, 2-heptanone (a ketone) was identified as a significant contributor to oxidative off-flavours, associated with sharp, fruity, or cheesy notes arising from fat oxidation (Gao et al., 2023; Wang et al., 2023). Similarly, sonicated milk and cheese have shown increased ketone and aldehyde production, contributing to oxidation-related flavour changes (Walstra et al., 2006). Moreover, benzaldehyde, which showed the highest relative abundance (2.26 ± 0.28 %) in the MTS LWE, typically imparts an almond-like flavour, though it is less directly linked to the rancid flavours characteristic of oxidised egg products (Liang et al., 2020b; Wang et al., 2023; Yu et al., 2023). These findings are consistent

Table 4
Profile of volatile compounds found in the TT and MTS LWE from the GC/MS detection together with their relative abundance, in %.

TT		MTS	
Compound	Relative abundance (%)	Compound	Relative abundance (%)
1-Penten-3-ol *	0.38 ± 0.13	1,5-Hexadiene	0.99 ± 0.15
Pentanal *	0.78 ± 0.41	1-Heptene	3.90 ± 0.47
2,5-Dimethyl-nonane	0.30 ± 0.08	Heptane	0.73 ± 0.30
3,5-Octadien-2-one *	0.68 ± 0.14	3-Methyl-1-butanol *	0.38 ± 0.15
		Styrene	3.58 ± 3.46
		2-Heptanone *	0.44 ± 0.10
		Benzaldehyde *	2.26 ± 0.28
		1-Heptanol *	0.22 ± 0.02

* Main compounds identified as contributors to oxidative off-flavours in food products, as reported in the scientific literature.

with oxidative profiles observed in other US-treated food products, such as plant-based emulsions (Dávila-Rodríguez et al., 2019) and meat emulsions (Zheng et al., 2022), where ketones and aldehydes increased due to lipid oxidation pathways. Therefore, MTS treatment likely induced a greater production of oxidative byproducts. Although these were not classical oxidation markers, their presence was unique to MTS samples, and the higher concentration of these compounds, with significant differences ($p < 0.05$) observed in the secondary oxidation compounds, suggested a distinct oxidative profile compared to untreated and TT LWE. Consequently, the higher abundance of oxidative compounds, such as 2-heptanone and benzaldehyde, along with potential synergistic effects, likely accentuated the perception of oxidative off-flavour in the omelette prepared with MTS LWE after cooking, as observed in the sensory characterisation (see Section 3.1).

3.4. Texture characterisation

Compression and cutting strength tests were performed in the omelettes made from the treated (MTS and TT) and commercial LWE samples to obtain respective texture properties. Results shown in Fig. 3 revealed that the omelette made with the MTS egg resulted in a significantly higher ($p < 0.05$) compression strength when compressed (43.07 ± 5.68 kPa) and reached a significantly higher maximum cutting strength (8.67 ± 0.84 kPa) compared with the omelette samples processed using thermal treatments (TT and control). Moreover, no significant differences ($p < 0.05$) were found between omelettes made with LWE subjected to thermal pasteurisation treatments. A possible explanation of the higher forces needed for the compression and cutting of the omelette made with MTS LWE can be found in the work by Beitia et al. (2025), where a physicochemical characterisation of LWE treated with MTS was performed. Firstly, a more elastic gel was found from the rheological oscillation tests performed to obtain information about the gelation dynamic of the LWE, showing higher values of the elastic modulus (G') and viscous modulus (G'') compared to those observed in thermal and untreated LWE. Moreover, it was found that MTS led to the unfolding of some LWE proteins (other than ovalbumin) that was not found by thermal treatment; as shown by both direct (asymmetric flow field flow fractionation, A4F) and indirect (surface hydrophobicity and sulfhydryl group determinations) analysis methods (Beitia et al., 2025). Consequently, new physical interactions, such as hydrogen bonds, ionic interactions, or disulfide bonds can originate during the coagulation process during omelette preparation, affecting the protein aggregation,

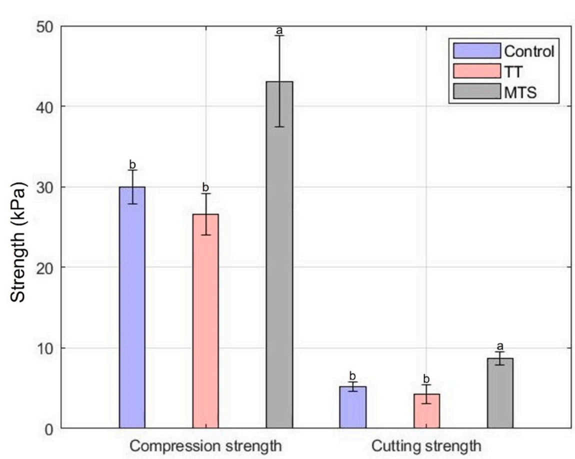

Fig. 3. Comparison of the texture analyses (compression strength and cutting strength) performed in the omelettes made from MTS (black) and TT (red) LWE and the omelette made from a commercial thermally pasteurised (control) sample (blue). The height of the bars represents the strength mean values, in kPa, of three independent biological replicates and the error bars show the SD. Different letters indicate a significant difference ($p < 0.05$).

and resulting in a strengthened gel network (Arzeni et al., 2012; Beitia et al., 2025; Mine, 1995; Paraskevopoulou et al., 2000). This effect was also reported in US-treated egg proteins, finding improved gelation properties after the sonication treatment due to an improved protein aggregation (Xue et al., 2021). Similarly, studies have demonstrated that US processing of EW proteins increased gel strength and elasticity, providing a firmer structure in final food applications (Zhang et al., 2017).

Therefore, texture plays a crucial role in taste perception and consumer preferences, often being a key factor in food acceptance or rejection. The ideal texture varies depending on the type of food; for omelettes, softer textures are generally preferred (Espina et al., 2014; Jeltema et al., 2015). Therefore, optimising formulations with addition of incorporating moisture-retaining ingredients could help balance firmness and improve consumer acceptance (Li-Chan et al., 2013). However, the reported increase in gel strength is desired in the texture of some food products, such as egg tofu or surimi products (Jin et al., 2021; Zhang et al., 2019). Previous research, related to such products, has focused on the improvement of the gelling properties of heat-induced EW gels using food additives, like xanthan gum (0.06 % w/w) (Zhang et al., 2019) or phosphates (sodium pyrophosphate and sodium tripolyphosphate) (Jin et al., 2021). Both additive incorporations provided desired properties to the EW gels, such as higher hardness and elasticity. The use of such food additives in the European Union (EU) must be declared on the food label with the respective E-number, according to Regulation (EU) No 1169/2011 on the provision of food information to consumers. However, this suggests a double benefit to the use of MTS in egg products through the production of a microbiologically safe product that additionally has improved gelling properties without the need for additives (clean label).

3.5. MFA

Considering the overall MFA configuration, the results from overall liking, RATA, omelette colour, flavour, texture, and VOCs presented RV values of 0.878, 0.684, 0.878, 0.821, 0.918, and 0.972, respectively, which indicates that these sets of data projected the samples into the MFA space in a very similar way (Table S.5, see Supplementary). The RV coefficients (varying from 0 to 1) indicate also the strength of the relationship between two sets of variables. The RV coefficients for overall liking revealed a very strong association with omelette colour (RV = 0.911), and texture (RV = 0.861; $p < 0.05$). The MFA plot, shown in Fig. 4, presents the first two dimensions of the MFA consensus, explaining 99.35 % of the variability of the experimental data representing the axes accounting for the most variance in the data, which indicates that they collectively captured the vast majority of the total variability in the data. Therefore, this high percentage suggested that most of the significant information was effectively represented within this two-dimensional space and that the samples were clustered into three groups: controls, TT, and MTS.

The TT sample was associated with several colour values, high values of L^*, a^*, and b^* on the bottom of the omelette, and of a^* and b^* on the centre of the omelette, in addition to high egg odour, and overall liking. This shows a correlation between these attributes to the TT sample and overall consumer liking. They were associated with a soft, crispy, silky, and airy texture, salty taste, the consumer perception of colour as greyish, light, and green colour, and high instrumental values of b^* values on the top of the omelette. Lastly, the MTS sample is associated with a sulphur-like and metallic odour, tough/rubbery texture, metallic taste and high values for oxidation, for both texture characteristics (cutting and compression) and a whiter (W^*) top of the omelette. Not all these variables were significantly different between the omelettes. Previous research by the authors has shown that treating LWE with MTS improved the foaming properties (foaming capacity and foaming stability) and emulsifying properties (emulsion stability) (Beitia et al., 2025). These enhanced techno-functional properties suggested its

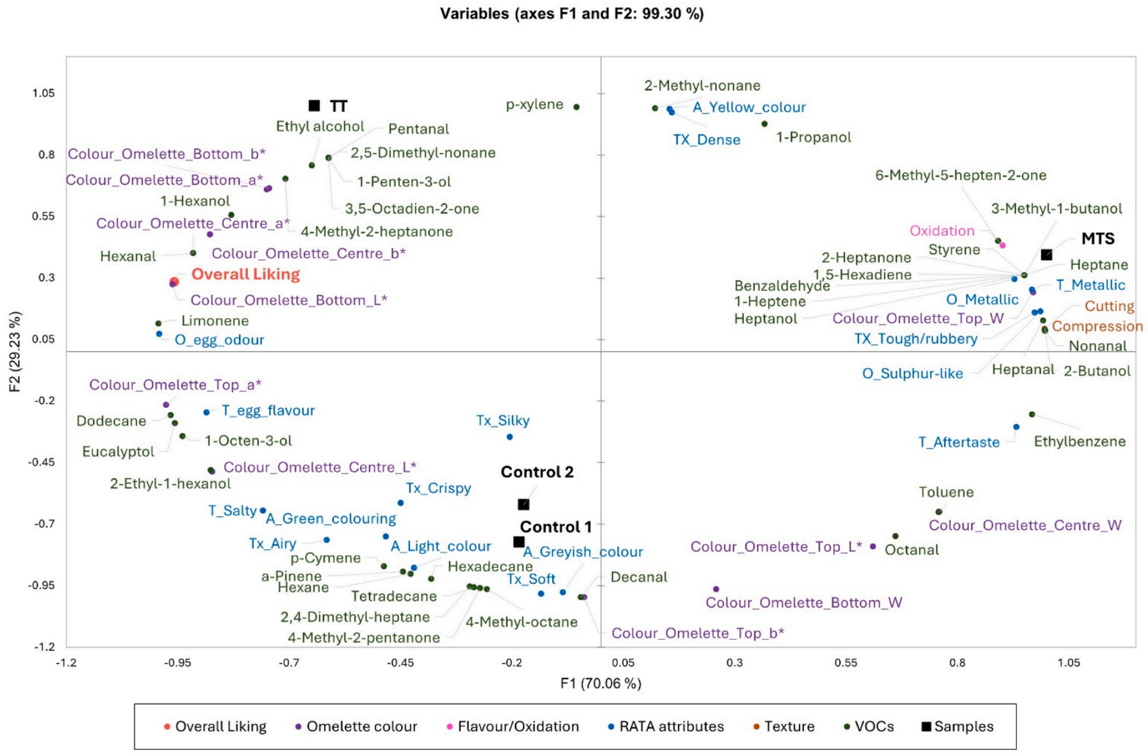

Fig. 4. Samples and attributes projections of dimensions 1 and 2 from the MFA applied to data from LWE instrumental colour, Omelette instrumental colour, texture features, flavour characterisation, RATA sensory profiling and overall liking. Abbreviations are TT = thermal treatment, control = commercial, and MTS = manothermosonication. (A) = appearance, (O) = odour, (T) = taste and (Tx) = Texture.

potential application in aerated egg-based products such as meringues, cakes, or mousses; as well as in emulsified products like mayonnaise, dressings, or egg-based sauces, where emulsion stability is crucial. However, the results from this study indicated that, while MTS treatment enhanced certain functional properties of LWE, such as foaming and emulsifying, it also led to distinct texture characteristics in omelettes prepared from MTS LWE, such as a firmer structure and enhanced gelling properties, but with higher oxidation levels. As a result, from a formulation perspective, MTS-treated LWE may still be suitable for certain applications where firmer textures are desirable, such as egg tofu or surimi products. Moreover, culinary strategies could help to mask the off-flavour attributes associated with the lipid oxidation, such as the incorporation of ingredients like herbs or spices.

4. Conclusions

Omelettes prepared with MTS-treated LWE were associated with metallic and sulphur-like odours and tastes, along with a firmer and more elastic texture compared to thermally pasteurised samples, which had higher overall taste scores and softer textures preferred by consumers. Likewise, volatile analysis revealed that oxidation-related compounds, particularly benzaldehyde and 2-heptanone, were in higher concentration in MTS samples, likely contributing to the observed sensory differences. Despite these sensory challenges, MTS resulted in a strengthened gel, suggesting its potential for applications where firmer gel structures are desirable, such as egg tofu or protein-enriched egg-based formulations. Future research should focus on optimising MTS parameters to mitigate oxidation effects, while maintaining its techno-functional benefits. Additionally, assessing industrial scalability, process feasibility, and equipment integration will be crucial to support the industrial application of MTS treatment.

Ethical statement

This study was approved by the Ethical Committee of the Faculty of Sciences, University of Porto, Portugal (authorisation number CE2023/P64). Complete confidentiality guaranteed adherence to the Helsinki protocol and informed consent was confirmed by the participants at the beginning of the study. This statement is indicated in the Material & Methods section of the manuscript. The informed consent explained the details of the study, the study's purpose, the protocols for protecting the rights and privacy of the participants, possible benefits, potential risks, and that the participation is voluntary. The informed consent is described below, in German and its translation into English.

CRediT authorship contribution statement

Enrique Beitia: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Aline Silva:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Grigorios Mavros:** Validation, Methodology, Investigation. **Frank Schilling:** Methodology. **Xiaoai Guo:** Writing – review & editing, Methodology. **Athanasios Mallouchos:** Writing – review & editing, Methodology, Investigation. **Volker Heinz:** Writing – review & editing, Resources, Funding acquisition. **Célia Rocha:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Rui C. Lima:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Dorothee Frickhofen:** Writing – review & editing, Methodology, Investigation. **Charalampos Proestos:** Writing – review & editing, Methodology, Investigation. **Lisa Methven:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Vasilis Valdramidis:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Luís M. Cunha:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Kemal Aganovic:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fufo.2025.100634.

Data availability

Data will be made available on request.

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