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Development and evaluation of ready-to-eat extruded oat gels as a dietary fiber delivery system

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ABSTRACT

Inadequate dietary fiber intake is a global health concern, necessitating innovative fiber-rich food solutions. This study aimed to develop and characterize a ready-to-eat (RTE) oat gel using a commercial extruded oat ingredient (EOI) for enhanced dietary fiber and polyphenol delivery. A comparative analysis with oat flour assessed their nutritional, physicochemical, and functional properties. EOI gels exhibited higher dietary fiber (3.33g/100g wet matter vs. 2.01 g/100g wet matter) and total phenolic content (2.32 vs. 0.97 mg gallic acid/mL), with lower least gelation concentration (LGC). Textural analysis profile (TPA) and back extrusion showed that EOI produce gels with enhanced firmness, cohesiveness, hardness and gumminess. EOI gels present significantly higher values ($P < 0.05$) in antioxidant, metal-chelating, antidiabetic, and hypocholesterolemic activities. Sensory evaluation indicated greater acceptability in texture and taste. In conclusion, the extruded oat ingredient is a promising functional ingredient for fiber-rich RTE food gels, offering enhanced bioactivity, improved texture, and sensory appeal, addressing dietary fiber deficiencies with a convenient and palatable solution. Future research should explore shelf-life and stability for commercial applications.

1. Introduction

The increasing prevalence and incidence of non-communicable diseases (NCDs) related to diet, such as obesity, diabetes or metabolic syndrome, have highlighted the importance of diet and nutrition in the world's population (Granato et al., 2020). To help prevent the onset of these pathologies, there is a growing interest in the food industry in the development of foods that provide health benefits beyond basic nutrition, the so-called functional foods (Granato et al., 2020).

On the other hand, modern lifestyle patterns have increased the consumer's demand of ready-to-eat (RTE) foods due to their convenience and the short time required for preparation. However, many RTE products have a high sugar and salt content (Brennan et al., 2013). Therefore, they are considered energy-dense but nutritionally poor foods whose consumption could have a negative impact in people's health (Brennan et al., 2013). A possible strategy to address both issues is the development of RTE foods with a healthier profile, incorporating functional ingredients such as vitamins, minerals, polyphenols or dietary fiber (Guiné et al., 2020). It is well-reported that dietary fiber has an important role in the contribution to health maintenance. Some of its beneficial functions could be regulating cholesterol and blood glucose levels, promoting proper faecal bulk formation or supporting a healthy intestinal microbiota (Joye, 2020). Furthermore, increased fiber intake has been associated with benefits for various NCDs such as metabolic syndrome (Castro-Barquero et al., 2020).

Oats (*Avena sativa*) are a well-recognized cereal with substantial nutritional value, being rich in dietary fiber, essential vitamins, minerals, and antioxidants, making them an excellent ingredient for functional foods (Alemayehu et al., 2023; Zhang et al., 2020).

The extrusion process is a high-temperature and high-pressure cooking method that modifies starch and fiber properties enhancing the digestibility of fiber in cereals and pulses and improve their techno functional properties (Orozco-Angelino et al., 2023). Fig. 1 summarizes the procedure of extrusion process in oat products and its advantages. This process is particularly promising for the development of whole grain flours, as it preserves all nutritional properties (Espinosa-Ramírez

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et al., 2021). Additionally, extrusion can create new textures in cereals and legumes due to the gelatinisation of starch. Therefore it could be considered an interesting technique for formulating gels (Espinosa-Ramírez et al., 2021).

Considering this background, the main objective of this study was to characterize "Oatgoods", a commercial extruded oat-based ingredient (EOI) made from oat flour, rapeseed oil, rice protein, and salt, as a functional ingredient for the development of RTE food gels rich in fiber and polyphenols, as a healthy alternative to RTE foods, providing a suitable product to obtain daily fiber intake and with bioactive properties, that can enhance health promotion. To achieve this task, a comparative study was conducted using oat flour as control, and their nutritional value and physico-chemical and functional properties were analyzed. Subsequently, gels were formulated using both flours, and their proximate composition, physico-chemical properties, and texture were evaluated. Additionally, their functional potential was assessed through *in vitro* assays for antioxidant, metal-chelating, antidiabetic, and hypocholesterolemic activities. Finally, consumer acceptance was analyzed through a sensory evaluation.

2. Materials and methods

2.1. Chemicals and reagents

Oatmeal, dried blueberries, vanilla, dates, erythritol, skimmed milk, lemon juice and sunflower oil were purchased in Mercadona, a Spanish commercial shop, and "Oatgoods", the extruded oat-based ingredient (EOI) were obtained from Myllyn Paras, part of Lantmännen Cerealia (Hyvinkää, Finland). Reagents for analytic assays were purchased from Sigma (MO, USA).

2.2. Flours characterization

2.2.1. Sample preparation and nutritional value

Oatmeal and EOI were grounded in a grinder (Moulinex, France) to pass through a 1 mm sieve. The nutritional value was obtained from the labels of the commercial products (Fig. S1). 20 mg/mL dilutions of oat flour samples were used to measure total polyphenol content by Folin Ciocalteau method with the modifications of Otero et al. (2019), results were expressed as mg gallic acid/mL and mean values were reported. Energy values in kilocalories (kcal)/100 g flour were calculated using Atwater factors: 4 kcal/g for carbohydrates and proteins, 9 kcal/g for fats, and 2 kcal/g for fiber.

2.2.2. Physicochemical properties

Moisture of flours were determined with a thermobalance (HB43 Halogen, Metter Toledo, USA) following the instructions of the equipment. Water activity (a_w) was measured with an a_w meter (Aqualab® 4Tev, Meter Food, USA). A 0.1 g/mL suspension of flours with double-distilled water was performed prior to measuring the pH with a pH meter (Mettler Toledo, USA). All measurements were carried out at 25 °C in triplicates and results were expressed by means.

2.2.2.1. Bulk density. Bulk density were calculated according to He et al. (2020) protocol. For bulk density, 10 mL of flour was weighted in a 10 mL graduated test tube. The bulk density was calculated as follows:

$$Bulk\ density = \frac{Mass\ of\ flour\ (g)}{Volume\ of\ flour\ in\ test\ tube\ (mL)}$$

2.2.2.2. Fluids holding capacity. Water holding capacity (WHC) was measured according to He et al. (2020) procedure with slight modifications. 0.5 g of flour and 10 mL of double-distilled water were mixed at 25 °C and submitted to agitation for 60 min. The mixture was introduced in an already weighted tube and then centrifuged at 2320×*g* for 15 min at 4 °C. Supernatant was discarded and the centrifuge tube with the soaked sample were weighted. WHC was calculated with the following formula:

$$WHC = \frac{mass\ of\ wet\ flour\ (g) - mass\ of\ dry\ flour\ (g)}{mass\ of\ dry\ flour\ (g)}$$

Oil holding capacity (OHC) and Milk holding capacity (MHC) were performed following the same procedure as WHC but with sunflower oil and skimmed milk respectively. Results were expressed as g water or oil, or milk/g dry flour and all assays were conducted in triplicate and mean values were reported.

2.2.2.3. Water solubility index (WSI). Water solubility index (WSI) was determined following the Chen et al. (2013) protocol. In short, 1 g of flour was weighted and mixed with 10 mL of double-distilled water. The mixture was submitted to constant stirring for 60 min and then centrifuged at 1006×*g* for 10 min at 4 °C. Supernatants were collected, cooled at.

−80 °C and then freeze dried in a freeze-drier (Scanvac Coolsafe, Labogene, Denmark) for at least 4320 min. WSI was determined with this formula:

$$WSI = \frac{Mass\ of\ freeze\ dried\ supernatant\ (g)}{Mass\ of\ dry\ flour\ (g)} x100$$

Results were expressed as g dry supernatant/100 g dry flour. All measurements were performed at triplicate with mean values reported.

2.2.3. Color parameters

Color was analyzed with a Minolta handheld colorimeter (CR-400,

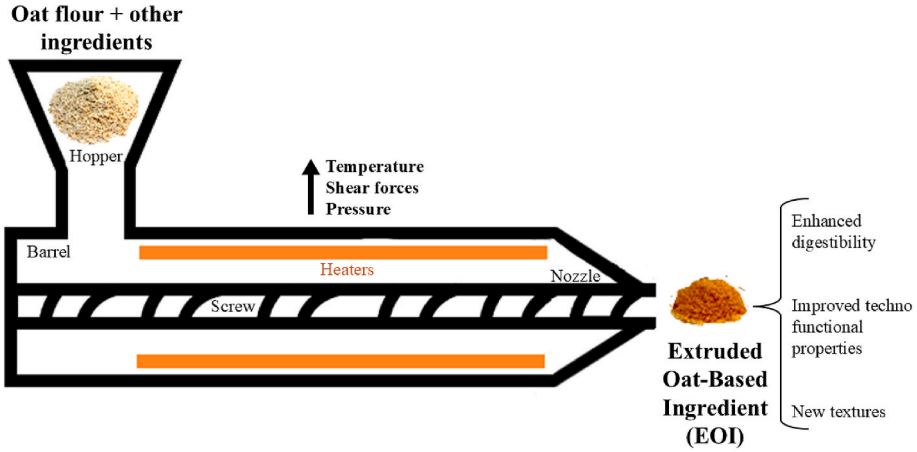

Fig. 1. Schematic diagram of oat extrusion and the advantages of the extruded product.

Konica Minolta, Japan) calibrated by reading a white background calibration plate (L* = 97.43, a* = 4.38, b* = 4.09). To measure the colour of the flours, they were placed in a specific annex for powdered products (1829-751 Space for Granular Materials CR-A50) and the gels in a specific annex for viscous samples (7600-0000-1719 Petri Dish Dispenser for CR-400), both on a white surface. Results were expressed with CIEL*a*b* parameters and Chroma (C*), hue(h) and difference of Color (ΔE) were calculated using these formulas:

$$\text{Hue } (^\circ) = \arctan(b^*/a^*)$$

$$\text{Chroma } (C^*) = ((a^*)^2 + (b^*)^2)^{1/2}$$

$$\text{Difference of Color } (\Delta E) = ((\Delta a^*)^2 + (\Delta b^*)^2 + (\Delta L^*)^2)^{1/2}$$

L* is the luminosity parameter (Black (0) to White (100)), a* is redness (Green (−60) to Red (+60)) and b* is yellowness (Blue (−60) to Yellow (+60)). The hue scale ranges from 0 (red), 90 (yellow), 180 (green) to 270 (blue). Chroma provides information on the purity of the Color: A C* value close to zero means low purity Color, close to grey. Conversely, high C* values correspond to high purity spectral Colors (Abebe & Ronda, 2014). All measurements were performed in triplicate and mean values were reported.

2.2.4. Techno functional properties

2.2.4.1. Swelling capacity (SwC). Swelling capacity was evaluated based on Chen et al. (2013) procedure. 0.2 g of flour was weighted in a 25 mL test tube. Then, 10 mL of double-distilled water was added and then the mixture was left to soak for 1080 min at 25 °C. After this, final volume of sample was measured. Swelling capacity was calculated as follows:

$$SwC = \frac{volume\ of\ wet\ flour\ (mL)}{mass\ of\ dry\ flour\ (g)}$$

Results were expressed as mL of wet flour/g dry flour and all measurements were performed in triplicate.

2.2.4.2. Emulsifying capacity (EmC). Emulsifying capacity (EmC) was analyzed according to Yang et al. (2018) with some modifications. 1 g of sample was weighted and then mixed with 15 mL of double-distilled water and 15 mL of sunflower oil. The mixture was dispersed with a homogenizer (ULTRATURRAX T25, IKA, Germany) for 3 min at 25 °C. Emulsions were centrifuged for 5 min at 4000×*g* at 4 °C. The emulsion layers were collected and measured in a test tube and the emulsion capacity was calculated as follows:

$$Emulsifying\ Capacity\ (\%) = \frac{Volume\ emulsion\ layer}{Total\ volume} x\ 100$$

All measurements were carried out in triplicate and mean values were reported.

2.2.4.3. Foaming capacity (FmC). Foaming capacity (FmC) was determined following the Guimarães et al. (2020) protocol with some modifications. 1 g of flour was weighed, and 50 mL of distilled water was added. Then the mixture was homogenized with a homogenizer (Ultraturrax T25, IKA, Germany) for 5 min at 25 °C. Then, the solution was transferred to a 100 mL graduated test tube, where the initial and final foam volume was measured after 0.5min.

$$Foaming\ Capacity\ (\%) = \frac{Volume\ foam\ after\ 0.5\ min}{Total\ volume} x\ 100$$

All measurements were performed in triplicate.

2.2.4.4. Least Gelation concentration (LGC). Least gelation concentration (LGC) were carried out according to Friero et al. (2024) method with minor modifications. Different concentrations of flour (2, 4, 6, 10, 12, 14, 16, 20 % (w/v)) were dispersed with 10 mL of double-distilled water in a tube. Solutions were stirred vigorously and then were submitted to a thermal treatment of 15 min at 85 °C. Then, samples were cooled in an ice bath and then the tubes were inverted. The least gelation capacity was considered as the minimum concentration in which the sample form a gel that does not flow when inverted. All measurements were carried out in triplicate and mean values were reported.

2.3. Oat gel elaboration

Oat gels were made according to this recipe: In short, all dry ingredients were weighed and ground for 1 min in a grinder (Moulinex, France). They were then mixed with wet ingredients and the mixture were left to soak for 120 min at 4 °C. Samples were then subjected to a heat treatment at 95 °C for 15 min with constant stirring and cooled in an ice bath. Finally, they were stored at 4 °C until further use.

2.4. Proximate composition and physico-chemical properties

2.4.1. Proximate composition

The proximate composition of the gels was determined according to AOAC standard methods: AOAC official method 925.10 for moisture, AOAC official method 923.03 for ashes, AOAC official method 979.06 for protein and AOAC official method 962.09 for dieatry fiber (Association of Official Analytical Chemists (AOAC), 2000). Total lipids were measured using the Folch method (Folch et al., 1957). Total carbohydrates were calculated by difference. All results were expressed in g/100g wet matter, and assays were performed in triplicate.

2.4.2. Physico-chemical parameters

Total polyphenol content, pH, a_w, color and bulk density were performed following the same methodology as in flour characterization.

2.4.2.1. Syneresis rate. Syneresis rate was determined by the method of Brückner-Gühmann et al., (2019a) with slight modifications. Briefly, 10 g of gel were weighed into a 15 mL tube and centrifuged at 500×*g* for 15 min at 20 °C. Supernatants were then recollected and weighed. Syneresis rate was calculated as follows:

$$Syneresis\ rate = \frac{(Mt - Ms)}{Mt} * 100$$

Ms is the supernatant mass, and Mt is the whole mass of the gel. Results were expressed as g supernatant/100 g wet matter and measurements were performed in triplicate.

2.5. Textural properties

2.5.1. Apparent viscosity

Apparent viscosity was analyzed by using a viscometer (VISCO™, ATAGO, Japan) sweeping at different angular speeds (0.2 s^{-1} to 1.6 s^{-1}) at 20 °C. Three independent samples of each gel were measured, and the obtained results were expressed in Pa.s.

2.5.2. Back extrusion

Textural properties of flours forming firm gels under refrigerated conditions were evaluated by back-extrusion following the methodology of Espinosa-Ramírez et al. (2021) with some adaptations. Texture analyses were performed using a TA.XTplus texture analyser (StableMicro Systems, Godalming, UK) with a 5000 g load cell and equipped with a 35 mm diameter acrylic cylindrical probe. Gels were poured into cylindrical pyrex containers (55 mm diameter, 68 mm height) and the test was carried out under the following conditions: Pre-test speed and test speed: 1 mm/s, post-test speed: 10 mm/s, distance to the sample: 30 mm and sample temperature: 20 °C. The parameters extracted from the test were defined as Makroo et al. (2019):

Firmness: Is the maximum force reached during the first compression

cycle and indicates how hard the sample is when compressed. It is expressed in Newtons (N).

Consistency: Is the area under the force–time curve up to the peak force and reflects the total energy required to deform the sample during the initial compression. It is expressed in Newton-seconds (N·s).

Cohesiveness: Is the maximum force recorded during the return portion of the cycle and indicates how well the sample holds together after compression. It is expressed in Newtons (N).

Work of Cohesion: Is the area under the curve in the negative region during probe return and represents the energy required to pull the probe away, reflecting adhesive and cohesive properties. It is expressed in Newton-seconds (N.s).

All measurements were carried out six times and mean values were reported.

2.5.3. Texture Profile Analysis (TPA)

Texture profile analysis (TPA) was conducted following Abebe & Ronda. (2014) method with some modifications. Gels at 20 °C were introduced into cylindrical pyrex containers (55 mm diameter, 68 mm height) and a texture analyzer (TA-XT2i, Stable Micro System, UK) equipped with a 5000g load cell and a 35 mm tall stainless steel cylindrical probe using a penetration speed of 2 mm/s and a deformation of 75 %. The parameters determined in the assay were descripted as Rahman et al. (2021):

Hardness: Defined as the peak force required to achieve a specified deformation during the first compression cycle (first bite). Expressed in Newtons (N).

Adhesiveness: Represents the negative force area (A3) following the first bite, indicating the work needed to detach the compressing probe from the sample. Expressed in Newton-meters (N·m). Negative values reflect stickiness or adhesiveness.

Springiness: Measures the extent of structural recovery between the end of the first compression and the start of the second. It reflects how much the sample regains its original form post-compression. Expressed in seconds or meters (s or m).

Gumminess: Applicable to semi-solid products, defined as the product of hardness and cohesiveness. Expressed in Newtons (N). Indicates the energy required to disintegrate the sample for swallowing; higher hardness yields higher gumminess.

Resilience: The ratio of the area during withdrawal (decompression) to the area of the first compression (A3/A1), measured immediately after the first penetration. Requires equal penetration and withdrawal speeds. Indicates immediate recovery capability.

Six measurements were carried out for each sample and mean values were reported.

2.6. Biological activities

2.6.1. Antioxidant and metal-chelating assays

2.6.1.1. Sample preparation. All gels were freeze-dried in a freeze-dryer (Scanvac Coolsafe, Labogene, Denmark). For the determination of antioxidant and metal chelating activites, 40 mg/mL dilutions of freeze-dried gels, oat flour or EOI were prepared with double-distilled water, shaken with constant stirring for 60 min at 25 °C and then centrifuged at 5000×*g* for 5 min. Supernatants were collected and a 1/100 (v/v) dilution were performed for Oxygen Radical Absorbance Capacity (ORAC) assays. All samples were stored at −20 °C until use.

2.6.1.2. Antioxidant activity assays. The antioxidant properties of oat samples were assessed through 4 assays: (i) DPPH free radical-scavenging activity was determined according to Bersuder et al. (1998) and results were expressed as % of inhibition. (ii) Ferric Reducing Antioxidant Power (FRAP) method, based on Chen et al. (2010), in which results were expressed as mmol Trolox equivalents/L. (iii) ABTS assay were performed according to Re et al. (1999) method where results were expressed as Trolox equivalent antioxidant capacity (TEAC) values and (iv) ORAC assay, adapted from López-Martínez et al. (2024) in which results were expressed as mmol of Trolox equivalent/g dry matter. 20 mg/mL dilution in ethanol of Butylhydroxytoluene (BHT) was the positive control for DPPH and FRAP, 4 mmol/L solution of ascorbic acid for ABTS and 1.5 μmol/L solution of tryptophan for ORAC. All assays were performed in triplicate and mean values were reported.

2.6.1.3. Metal-chelating activity assays. Ferrous Ion Chelating Activity was assessed according to Zheng et al. (2019), Zinc Ion Chelating Activity were performed following the protocol of Udechukwu et al. (2018) and Copper Ion Chelating Activity were carried out based on the method of Kubglomsong et al. (2018). Results were expressed as % chelation using 0.1 mg/mL solution of Ethylenediaminetetraacetic acid (EDTA) as positive control. All assays were conducted in triplicate, and mean values were reported.

2.6.2. Antidiabetic assays

α-glucosidase inhibition assay were conducted as detailed Wei et al. (2021). Results were expressed as % of inhibition using 5 mg/mL solution of acarbose as positive control. All measurements were carried out by triplicates and mean values were reported.

2.6.3. Hypocholesterolemic activity assay

The hypocholesterolemic activity of gels was analyzed following the Navarro del Hierro et al. (2022) method. through *in vitro* gastrointestinal digestion. A dietary fats simulation mixture (3 mg lecithin, 8 mg cholesterol and 80 mg refined olive oil) was prepared and mixed with 5 mg of gels (samples) β-sitosterol (positive control) or double-distilled water (negative control). Subsequently, gastric digestion was performed by adding 2.2 mL of gastric solution (150 mmol/L NaCl, 6 mmol/L $CaCl_2$ and 0.1 mmol/L HCl pH 2.5) and 0.225 mL of fresh gastric enzyme extract (gastric lipase 16 mg/mL and pepsin 29.4 mg/mL in gastric solution). The mixture was stirred at 250 rpm in an orbital shaker at 37 °C for 45 min. Then, intestinal phase was initiated by including 0.95 mL of simulated biliary solution (0.050 g of lecithin, 0.125 g of bile salts, 0.25 mL of 325 mmol/L $CaCl_2$ solution, 0.75 mL of 3.25 mol/L NaCl solution and 5 mL of Trizma-maleate buffer 100 mmol/L pH 7.5) and 0.225 mL of pancreatin extract (15.6 mg/mL in Trizma-maleate buffer 100 mmol/L pH 7.5) to the mixture. This mixture was incubated at 37 °C with stirring at 250 rpm for 60 min. After digestion, the mixture was centrifuged at 2688×*g* for 40 min. The aqueous micellar phase containing solubilized cholesterol was collected for analysis. Cholesterol quantification was performed using high-performance liquid chromatography with diode-array detection (HPLC-DAD) as described by Kolarič and Šimko (2020) with slight modifications. An ACE 3 C18-AR column (150 mm × 4.6 mm, 3 μm particle size) was used for the assay under the following conditions: isocratic elution with a water/methanol (5:95, v/v) mobile phase at a flow rate of 1.2 mL/min, a column temperature of 35 °C, an injection volume of 20 μL, and a detection wavelength of 205 nm.

Bioaccessibility was calculated as:

$$\textit{Cholesterol bioaccesibility}\ (\%) = \left(\frac{\textit{Cholesterol in micellar phase}}{\textit{Cholesterol in digestion medium}}\right) \text{x } 100$$

The hypocholesterolemic potential was assessed by evaluating the bioaccessible cholesterol levels across different sample groups (sample, negative and positive control). A significant decrease in bioaccessible cholesterol levels was indicative of a potential hypocholesterolemic effect.

2.7. Sensory analysis

Sensory analysis of gels was carried out according to an hedonic 10-

point scale (1-extremely dislike it, 10 – extremely like it) (Brückner-Gühmann et al., 2019b). A total of 103 volunteers from the Food Science Research Institute (CIAL-CSIC) participated in the study after being informed about the ingredients and potential allergens. All participants voluntarily agreed to evaluate the samples. The samples were presented in transparent cylindrical containers (1.5 cm in diameter, 3 cm in height) at 25 °C and served with a spoon. Tape water was provided for palate cleansing. Color, taste, texture, and overall acceptability were the sensory attributes evaluated in the survey. The results were expressed as mean values.

2.8. Statistical analysis

An analysis of variance (ANOVA) followed by Tukey's study range test was performed, with a significance level of $P < 0.05$ for statistical analysis of the results. Different letters mean significant differences with a significance level of $P < 0.05$. The statistic program used was Minitab (Minitab, LLC, USA).

3. Results and discussion

3.1. Flours characterization

According to the nutritional value in Table 1, it is shown that EOI has a higher content of fats which translates into an increase in caloric value. However, regarding the lipid profile, EOI presents higher unsaturated fatty acid content (90.5 % vs. 81.4 %) than oatmeal. This is because EOI has rapeseed oil in its composition. Rapeseed oil is one of the vegetable oils with the highest content of unsaturated fatty acids, standing out in oleic acid (63.7 %) linoleic acid (17.4 %) and γ-linolenic acid (6.8 %). Rapeseed oil is also rich in polyphenols, which could also explain the significantly higher ($P < 0.05$) polyphenol content in EOI (Chew, 2020) (2.38 ± 0.18a mg Gallic acid/mL > 1.21 ± 0.16 b mg Gallic acid/mL). The extrusion technique present in EOI manufacturing process affects in several parameters due to the thermal and shear effects on the material. First, it can increase the polyphenol content, as the molecular alteration produced could favour the release of these from their matrix and therefore increase their bioavailability (Šárka et al., 2021). In terms of color, the Maillard reaction produced in extrusion process impacts in the appearance of EOI. Maillard reaction is a non-enzymatic browning reaction between amino groups of proteins and carbonyl groups of sugars under high temperature and pressure, which produces numerous substances involved in aroma and flavour as well as brown pigments (Starowicz & Zieliński, 2019). EOI showed significantly higher ($P < 0.05$) redness (a*) (8.54 ± 0.58a >0.90 ± 0.01b) and yellowness (b*) (33.56 ± 0.14a >12.15 ± 0.02b), and significantly lower ($p < 0.05$) lightness (L*) (56.50 ± 0.17b < 83.10 ± 0.03a) compared to oat flour and a color difference (ΔE) greater than 5 (34.99 ± 0.13) which means that are perceptible to the human eye (Abebe & Ronda, 2014). Maillard reaction during extrusion likely caused the darker color of EOI (lower L*, higher a* and b*) since it is related with the development of darker flours (He et al., 2020) as can be perceived in Fig. 2A.

According to physico-chemical and techno functional parameters in Table 1, EOI has significantly more ($P < 0.05$) WSI (4.93 ± 0.41a g dry supernatant/100 g flour >4.00 ± 0.19 b g dry supernatant/100 g flour), WHC (4.56 ± 0.10a g water/g flour >3.07 ± 0.05 b g water/g flour) and MHC (4.99 ± 0.17a g milk/g flour >3.88 ± 0.09 b g milk/g flour) in comparison with oat flour. This increase in WSI, WHC and MHC in EOI is primarily attributed to the breakdown of granules and the resultant increase in starch granules disrupted by extrusion, due to thermal processing and shear stress in extrusion. The mechanical forces applied during grinding increase the specific surface area of oat flour, leading to enhanced hydration and water retention (Espinosa-Ramírez et al., 2021). Besides, the breakdown of starch particles into smaller units exposes more hydrophilic components, thereby facilitating hydrogen bond formation with water molecules (He et al., 2020). The promotion of hydrogen bond formation significantly enhances the capacity of EOI to form cold gels (Espinosa-Ramírez et al., 2021) as it is observed in the least LGC tests (Table 1), where EOI require a significantly ($P < 0.05$) lower concentration (11.33 ± 1.15b % < 17.33 ± 2.31a %) to form a gel compared to oat flour. Lower LGC indicates better gel-forming ability at lower concentrations, and the reduction of LGC in EOI is particularly advantageous for the development of food gels with improved texture, therefore for this reason, a gel was the food selected to develop in the next assays.

Table 1
Characterization of flours (N = 3, Mean ± SEM).

	Oat flour	EOI
Nutritional value[a]		
Fats (g/100g wet matter)	7	19
Saturated fats (g/100g wet matter)	1.30	1.80
Insaturated fats ratio (%)	81.43	90.52
Carbohydrates (g/100g wet matter)	59	47
Sugars (g/100g wet matter)	0.70	1.30
Dietary fiber (g/100g wet matter)	10	9
Proteins (g/100g wet matter)	14	15
Ashes (g/100g wet matter)	0.02	0.90
Energy (Kcal/100g wet matter)	375	439
Proximate composition.		
Moisture (g/100g wet matter)	10.63 ± 0.50a[b]	9.31 ± 0.10b
Phenolic Compounds (mg Gallic acid/mL)	1.21 ± 0.16b	2.38 ± 0.18a
Color parameters.		
Lightness (L*)	83.10 ± 0.03a	56.50 ± 0.17b
Redness (a*)	0.90 ± 0.01b	8.54 ± 0.58a
Yellowness (b*)	12.15 ± 0.02b	33.56 ± 0.14a
Chroma (C*)	12.18 ± 0.02b	34.63 ± 0.24a
Hue (h)	85.76 ± 0.05a	75.73 ± 0.89b
Color difference (ΔE)	34.99 ± 0.13	
Physico-chemical parameters		
pH	6.24 ± 0.06a	5.91 ± 0.07b
Water activity (a_w)	0.48 ± 0.00b	0.55 ± 0.00a
Bulk density (g flour/mL flour)	0.50 ± 0.00b	0.58 ± 0.00a
Water solubility index (WSI) (g dry supernatant/100g dry flour)	4.00 ± 0.19b	4.93 ± 0.41a
Water holding capacity (WHC) (g water/g dry flour)	3.07 ± 0.05b	4.56 ± 0.10a
Oil holding capacity (OHC) (g sunflower oil/g dry flour)	3.61 ± 0.08a	2.88 ± 0.21b
Milk holding capacity (MHC) (g skimmed milk/g dry flour)	3.88 ± 0.09b	4.99 ± 0.17a
Techno functional properties.		
Emulsifying capacity (%)	8.53 ± 0.46a	9.73 ± 1.01a
Foaming capacity (%)	9.33 ± 1.15a	7.33 ± 1.14a
Swelling capacity (mL wet flour/g dry flour)	4.17 ± 0.29a	4.67 ± 0.30a
Least Gelation Concentration (LGC) (%)	17.33 ± 2.31a	11.33 ± 1.15b

b EOI means Extruded Oat-based Ingredient.
[a] Directly obtained from commercial labels of products.
[b] Different letters mean significant differences (P < 0.05) between samples.

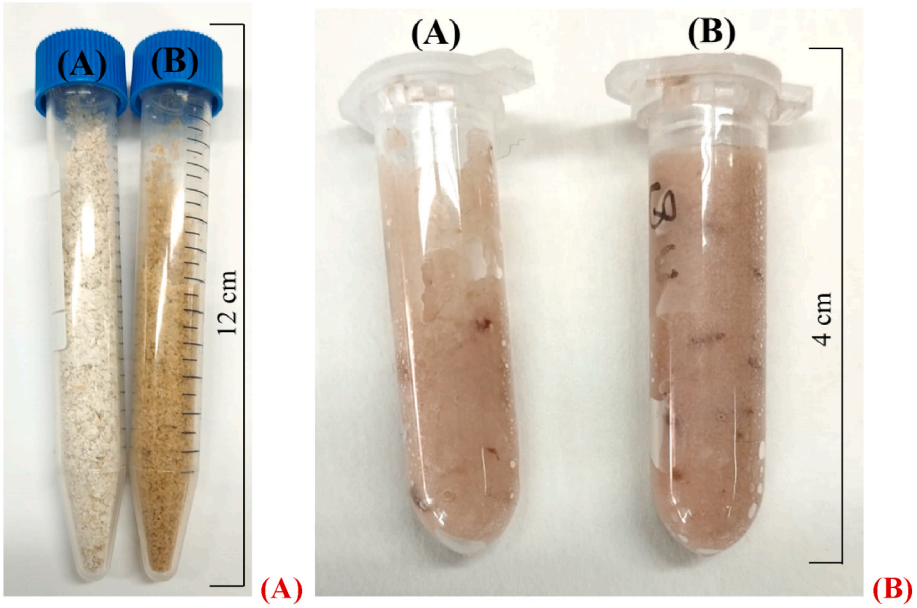

Fig. 2. A represent flour samples where (A) is oatmeal flour while (B) is Extruded Oat-based ingredient (EOI). B represents gel samples where (A) is oat gel while (B) is EOI gel.

3.2. Oat gel recipe

As can be perceived in Table 2, both gels have the same recipe varying only the oat source, being oat flour in the control gel and EOI in the gel of interest. The other ingredients were selected according to the following criteria:

Chickpea flour was added because it is a cheap legume with high protein content, which complements well the possible deficits in some essential amino acids that oatmeal may have, making the overall protein quality superior (Kumar & Pandey, 2020). Besides, dried blueberries (Skrovankova et al., 2015) and dates (Maqsood et al., 2020) were added as a source of fiber and antioxidant compounds, to provide added value to the product. Lemon juice was added as a natural preservative and erythritol and vanilla flavouring were added for their sweetening function.

3.3. Nutritional value and characterization of gels

Table 3 shows that the oat gel has significantly higher ($P < 0.05$) ash (0.25 ± 0.02 b g/100g wet matter< 0.30 ± 0.01a g/100g wet matter) and moisture content (82.67 ± 0.11 b g/100g wet matter <87.45 ± 0.97a g/100g wet matter) than the EOI gel. On the other hand, EOI gel has a significantly higher ($P < 0.05$) content of other nutrients than oat gel being two times higher in phenolic compounds (2.32 ± 0.69a mg Gallic acid/mL > 0.97 ± 0.12 b mg Gallic acid/mL). The increase in fiber content is mainly due to its manufacturing process since EOI is an ingredient obtained by extrusion. It has been observed that the use of this technique in whole grains and legumes generates a higher fiber content, especially soluble fiber (Orozco-Angelino et al., 2023). This is due to the gelatinisation of the starch granules, which lose their crystalline structure because of the high temperatures and shear forces of the processing, generating a retrogradation of this polysaccharide, converting it into soluble fiber (Sandrin et al., 2019). This process can also contribute in the release of proteins and polyphenols from the cereal matrix (Moisio et al., 2015).

Observing the color parameters, EOI gel exhibits significantly lower

Table 2
Oat gels recipe.

Gels recipes		
Ingredients	Oat Gel	EOI[a] gel
Oat Flour	12g	0g
Oatgoods	0g	12g
Chickpea Flour	7g	7g
Dried blueberries	9g	9g
Dates	2g	2g
Erythritol	2g	2g
Water	100 mL	100 mL
Lemon juice	2 mL	2 mL
Vanilla extract	0.5 mL	0.5 mL

[a] EOI means Extruded Oat-based Ingredient.

Table 3
Characterization of gels (N = 3; Mean ± SEM).

	Oat gel	EOI[a] gel
Proximate composition		
Moisture (g/100g wet matter)	87.45 ± 0.97a[b]	82.67 ± 0.11b
Carbohydrates (g/100g wet matter)	4.88 ± 0.98b	7.02 ± 0.05a
Dietary fiber (g/100g wet matter)	2.01 ± 0.06b	3.33 ± 0.01a
Soluble fiber (g/100g wet matter)	0.15 ± 0.02b	0.44 ± 0.01a
Insoluble fiber (g/100g wet matter)	1.86 ± 0.04b	2.88 ± 0.01a
Fats (g/100g wet matter)	3.50 ± 0.25b	4.59 ± 0.11a
Proteins (g/100g wet matter)	1.86 ± 0.03b	2.15 ± 0.12a
Ashes (g/100g wet matter)	0.30 ± 0.01a	0.25 ± 0.02b
Energy (kcal/100g wet matter)	62.48	84.63
Phenolic Compounds (mg Gallic acid/mL)	0.97 ± 0.12b	2.32 ± 0.69a
Color parameters	Oat gel	Oatgoods gel
Lightness (L*)	50.06 ± 1.25a	48.16 ± 0.53a
Redness (a*)	8.04 ± 0.14a	7.73 ± 0.07b
Yellowness (b*)	9.89 ± 0.20a	7.71 ± 0.07b
Chroma (C*)	12.75 ± 0.24a	10.92 ± 0.02b
Hue (h)	50.87 ± 0.19a	44.93 ± 0.51b
Color difference (ΔE)	5.97 ± 0.87	
Physico-chemical properties		
pH	4.00 ± 0.08a	4.22 ± 0.13a
Water activity (a_w)	0.997 ± 0.001a	0.992 ± 0.001b
Bulk density (g gel/mL gel)	0.92 ± 0.01a	0.93 ± 0.01a
Syneresis rate (g supernatant/100g wet matter)	0.27 ± 0.05a	0.00 ± 0.00b

[a] EOI means Extruded Oat-based Ingredient.
[b] Different letters mean significant differences ($P < 0.05$) between samples.

redness (a*), yellowness (b*), chroma (C*), and hue (h) compared to oat gel, resulting in a brownish appearance. This difference is perceptible to the human eye ($\Delta E = 5.97 \pm 0.87 > 5$) (Abebe & Ronda, 2014) as can be observed in Fig. 2B and could be related with the color of the starting flour.

Regarding physico-chemical properties (Table 3), both gels have no significant differences ($P < 0.05$) in the parameters pH, bulk density and lightness. However, the EOI gel has a significantly lower ($P < 0.05$) a_W (0.992 ± 0.001b $< 0.997 \pm 0.001$a) and syneresis rate (0.00 ± 0.00 b g supernatant/100g wet matter $<0.27 \pm 0.05$a g supernatant/100g wet matter). These results may be due to the fact that EOI generates gels whose structure is stronger because there is more interaction between its molecules, since there is a greater release of hydrophilic groups in the proteins and a greater connection of its starch granules (Garcia-Amezquita et al., 2019), which prevents the release of the retained water, producing a lower a_W and syneresis rate (Wang et al., 2019). This can be very beneficial because the reduction of these parameters could improve the shelf life of these gels.

In Fig. 3 it can be observed that both gels showed thixotropic behaviour, i.e. their viscosity gradually decreases with increasing shear rate as the shear rate increased until reaching an equilibrium phase at 1 s^{-1} in both gels (Ma et al., 2014), at which point the viscosity stabilised. Nevertheless, EOI gel showed much higher viscosity than the oat gel at low shear rates, and it is not until equilibrium is reached that the difference between the two gels is reduced. This may be because the oat goods gel has a stronger structure due to its higher soluble fiber content, which favours the formation of cold gels with strong structure (Sandrin et al., 2019). In this sense, other authors perceived these kind of behaviour in several oat products (Brückner-Gühmann, Banovic et al., 2019a; Xue et al., 2020).

Table 4 shows the texture profile of both gels. EOI gel is shown to have significantly differences ($P < 0.05$) for all parameters in back extrusion and significantly higher values ($P < 0.05$) for hardness (2.96 ± 0.11a N $> 1.33 \pm 0.09$ b N) and gumminess (2.59 ± 0.21a N $> 1.17 \pm 0.04$ b N) and significantly lower in adhesiveness (-8.12 ± 0.30 b N.s $< -2.50 \pm 0.33$a N.s) in TPA parameters than oat gel.

The extrusion of the EOI manufacturing process is probably mainly responsible for this increase in these textural characteristics. The release of soluble fiber due to the fragmentation of the starch granules as well as the exposure of the hydrophilic part of the proteins contributes significantly to the adhesiveness of the whole grain flour products (Espinosa-Ramírez et al., 2021). In addition, the possibility of increased cross-linking between these molecules leads to an increase in viscosity which is correlated with firmness, hardness, consistency and gumminess (Offiah et al., 2019) favouring the generation of more compact and less flowable gels. The generation of more compact and less flowable gels can be particularly beneficial for developing modified-texture gels for individuals with swallowing difficulties. Research has shown that

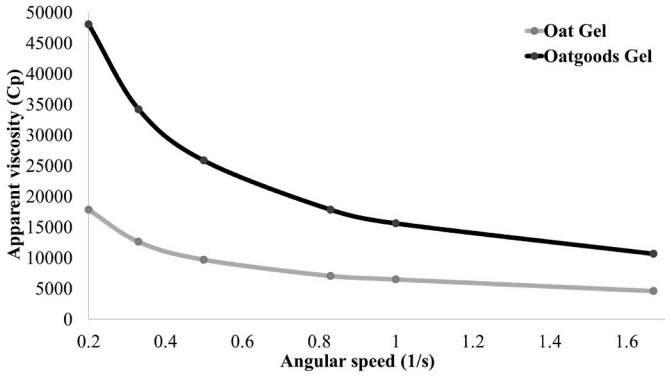

Fig. 3. Apparent viscosity (Cp) sweep at different angular speeds (s^{-1}) of gels at 25°C.

Table 4
Texture parameters of gels (N = 6; Mean ± SEM).

	Oat Gel	EOI[a] Gel
Back Extrussion parameters		
Firmness[c] (N)	2.38 ± 0.13b[b]	5.52 ± 0.97a
Consistency (N.s)	14.63 ± 1.19b	30.81 ± 2.20a
Cohesiveness (N)	−3.49 ± 0.84a	−8.37 ± 0.47b
Work of cohesion (N.s)	−3.90 ± 0.72a	−7.25 ± 0.31b
Texture Profile Analysis parameters		
Hardness[d] (N)	1.33 ± 0.09b	2.96 ± 0.11a
Adhesiveness (N.s)	−2.50 ± 0.33a	−8.12 ± 0.30b
Springiness (s)	0.90 ± 0.03a	0.90 ± 0.04a
Gumminess (N)	1.17 ± 0.04b	2.59 ± 0.21a
Resilience	0.02 ± 0.01a	0.01 ± 0.00a

[a] EOI means Extruded Oat-based Ingredient.
[b] Different letters mean significant differences ($P < 0.05$) between samples.
[c] Back extrusion parameters were defined as: Firmness: Is the maximum force reached during the first compression cycle and indicates how hard the sample is when compressed. Consistency: Is the area under the force–time curve up to the peak force and reflects the total energy required to deform the sample during the initial compression. Cohesiveness: Is the maximum force recorded during the return portion of the cycle and means how well the sample holds together after compression. Work of Cohesion: Is the area under the curve in the negative region during probe return and represents the energy required to pull the probe away, reflecting adhesive and cohesive properties.
[d] Texture Profile Analysis (TPA) parameters were defined as: Hardness: Defined as the peak force required to achieve a specified deformation during the first compression cycle. Adhesiveness: Represents the negative force area (A3) following the first bite, indicating the work needed to detach the compressing probe from the sample. Springiness: Measures the extent of structural recovery between the end of the first compression and the start of the second. It reflects how much the sample regains its original form post-compression. Gumminess: Applicable to semi-solid products, defined as the product of hardness and cohesiveness. Indicates the energy required to disintegrate the sample for swallowing; higher hardness yields higher gumminess.Resilience: The ratio of the area during decompression to the area of the first compression (A3/A1), measured immediately after the first penetration. Requires equal penetration and withdrawal speeds. Indicates immediate recovery capability.

increased cohesiveness is related to the extensibility of homogeneous foods, and it is hypothesized that highly cohesive fluids could be safer for this kind of population (Nishinari et al., 2019). Furthermore, cohesiveness, firmness, and adhesiveness have been identified as the most relevant organoleptic attributes for foods intended for people with swallowing difficulties (Ibanez et al., 2022), therefore it could be hypothesized that EOI could be a potential ingredient in the development of healthy and safer gels for people with swallowing disorders. Moreover, all these properties can contribute in the perception of creaminess in the final product, which can enhance palatability (Juvinal et al., 2023). This enhanced texture and stability not only make the product safer to consume but also more enjoyable, thus potentially increasing adherence to dietary recommendations and improving overall nutritional intake.

3.4. Bioactive properties of gels

According to Table 5, EOI gel has significantly higher values ($P < 0.05$) in all assays in antioxidant, metal-chelating, antidiabetic activities and demonstrates a significantly lower ($P < 0.05$) percentage of cholesterol bioaccesibility (9.10 ± 5.82b %$< 44.18 \pm 4.55$a %) in hypocholesterolemic capacity than oat gel, being lower than the positive control (35.4 %).

Regarding the composition, the antioxidant activity of this gels is probably due to the vitamin C in the lemon juice and the polyphenols. The major polyphenols will come from oats, such as avenanthramides (Zhang et al., 2020), and dried blueberries (Skrovankova et al., 2015). Besides, in the case of EOI, they would also come from rapeseed oil, as

Table 5
in vitro biological activity assays (N = 3; Mean ± SEM).

Biological activity assays	Oat gel	EOI[a] gel	Positive control[c]
Antioxidant assays			
ORAC (mmol trolox/g dry matter)	11.36 ± 2.88b[b]	17.47 ± 3.55a	955.05
ABTS (TEAC)	9.98 ± 0.44b	13.72 ± 0.43a	100
DPPH (% inhibition)	49.31 ± 2.48b	59.40 ± 0.73a	91
FRAP (mmol trolox/L)	2.89 ± 0.02b	3.39 ± 0.10a	18.71
Metal chelating assays			
Fe^{2+} (% Chelation)	21.73 ± 1.83b	70.47 ± 1.42a	100
Zn^{2+} (% Chelation)	29.11 ± 3.24b	52.96 ± 2.34a	100
Cu^{2+} (% Chelation)	68.64 ± 5.78b	81.11 ± 1.01a	100
Antidiabetic assay			
α glucosidase inhibition (% inhibition)	57.20 ± 0.66b	71.34 ± 2.57a	96.5
Hipocholesterolemic assay			
% Cholesterol bioaccesibility	44.18 ± 4.55a	10.80 ± 4.10b	35.4

[a] EOI means Extruded Oat-based Ingredient.
[b] Different letters mean significant differences ($P < 0.05$) between samples.
[c] 20 mg/mL dilution in ethanol of Butylhydroxytoluene (BHT) was the positive control for DPPH and FRAP, 4 mmol/L solution of ascorbic acid for ABTS, 1.5 μmol/L solution of tryptophan for ORAC, 0.1 mg/mL solution of Ethylenediaminetetraacetic acid (EDTA) for metal-chelating assays, 5 mg/mL solution of acarbose for antidiabetic assay and β-sitosterol for hypocholesterolemic assay.

there are several studies confirming its high polyphenol content (Chew, 2020), which would explain its significantly higher antioxidant activity. On the other hand, from the point of view of the structure, the extrusion of the processed EOI could impact of their polyphenols content. This technique can affect negatively in these compounds since it requires high temperatures and strong shear forces. Nevertheless, the bio accessibility of polyphenols can be enhanced by generating conjugates with the denaturalised proteins that favour their better absorption (Brennan et al., 2011) and would be reflected in a greater impact on the antioxidant capacity promoting their action against free radicals.

Polyphenols could also be responsible for the significantly higher antidiabetic assay. α-glucosidase is, together with α-amylase, one of the two main enzymes responsible for starch hydrolysis, therefore its inhibition favours a slower and more progressive degradation of this polysaccharide, preventing fast increases in postprandial blood glucose, which can be beneficial for people with diabetes (Wei et al., 2021). It has been previously reported that polyphenols can exert an inhibitory effect on this enzyme (Sun & Miao, 2020), which together with the presence of other substances that can retard starch digestion such as soluble fiber or β-glucans, could explain this increase in the anti-diabetic capacity of EOI gels.

The higher metal chelating capacity of the EOI gel may be related to the melanoidins produced in the Maillard reaction. Maillard reaction may have been developed both in the gel cooking process and in the extrusion process in the production of EOI, which could mean that more melanoidins could be produced. Melanoidins can chelate transition metals such as Fe, Zn or Cu, preventing them from generating reactive oxygen species (ROS), thus promoting antioxidant status in the body (Sharma et al., 2021).

Observing hypocholesterolaemic activity, the composition of EOI gel could have a major impact as this is mainly because of fibre. The effect of fiber on the prevention of cholesterol blood's accumulation is well researched in the literature (Joye, 2020). Moreover, oats have been characterised as a cereal whose constituents could contribute to this effect (Joyce et al., 2019). In fact, oat β-glucans have a health claim for their contribution to the prevention of hypercholesterolaemia (Mathews et al., 2020). In the case of EOI gel, rapeseed oil should also have influenced hypocholesterolaemic activity, as its fatty acid profile, rich in omega-3 fatty acids such as α linolenic acid, has been described as a very beneficial factor in the prevention of hypercholesterolaemia (Tang et al., 2022). Besides, extrusion favours the generation of soluble fiber via gelatinisation of starch granules and the release of total fiber from the matrix (Orozco-Angelino et al., 2023; Sandrin et al., 2019). Hence, it would also partly explain the increased hypocholesterolemic effect.

In summary, EOI gel has demonstrated significant bioactive potential in four key biological activities, suggesting its classification as a functional food that may help in the prevention of certain diet-related pathologies such as metabolic syndrome. Metabolic syndrome is characterized by a cluster of metabolic risk factors, including abdominal obesity, dyslipidemia, low levels of high-density lipoprotein cholesterol (HDL-c), hypertension, and insulin resistance. The bioactive properties of EOI gel could positively impact these risk factors. Additionally, it is well-reported that a diet rich in polyphenols and dietary fiber can contribute in the reduction of metabolic syndrome (Castro-Barquero et al., 2020). Thus, EOI gel could serve as an additional source of these nutrients.

3.5. Sensory analysis of gels

According to Fig. 4, EOI gel obtained significantly better results in texture and taste parameters ($P < 0.05$). In the case of taste, it is possible that the Maillard reaction during the EOI manufacturing process has generated pleasant flavour and aroma compounds, which have had a positive impact on the overall taste of the product (Starowicz & Zieliński, 2019). On the other hand, the better assessment of the texture is possibly related to the EOI gel being firmer and more consistent, according to the texture parameters, which is likely to be perceived as creamier and more palatable product (Juvinal et al., 2023). Nevertheless, both gels were rated positively in all parameters, mainly because both could be described as a creamy and quite sweet product. Creaminess is one of the most favourable sensory attributes since it usually means that the product has a desirable texture (Roobab et al., 2023). In fact, in a recent study (Brückner-Gühmann et al., 2019b) a sensory analysis was conducted of a fermented oatmeal gel and they found that the most important parameters determining a positive rating of the product were creaminess, smoothness and sweetness, which are properties that both gels have, therefore that means that oat goods gel could have a good commercial reception.

4. Conclusion

In conclusion, EOI, owing to its enhanced nutritional, functional, organoleptic, and bioactive properties, presents significant advantages over traditional oat flour. In this sense, EOI gels exhibited higher dietary fiber content, polyphenols and bioactivity, with improved texture and sensory appeal compared to oat flour gels. The utilization of EOI in the development of oat gels has shown potential for creating a functional ready-to-eat (RTE) food product that offers health benefits and favourable sensory attributes. This positions EOI as a promising ingredient for the food industry. The EOI gel emerges as a nutritious and convenient RTE food that functions as a dietary supplement, contributing to the daily intake of fiber and antioxidants with and improved texture, being suitable their incorporation to diet as breakfast products or snacks to increase fiber intake. Such properties make the EOI gel particularly suitable for helping in the management of non-communicable diseases (NCDs) like metabolic syndrome or swallowing disorders, thereby contributing to improved overall wellness. The comprehensive benefits provided by EOI underline its significance as an ingredient in developing innovative food products aimed at promoting health and managing specific health conditions. In future studies, shelf life and other bioactivities can be analyzed to ensure the food security and bioactivity of these functional EOI gels.

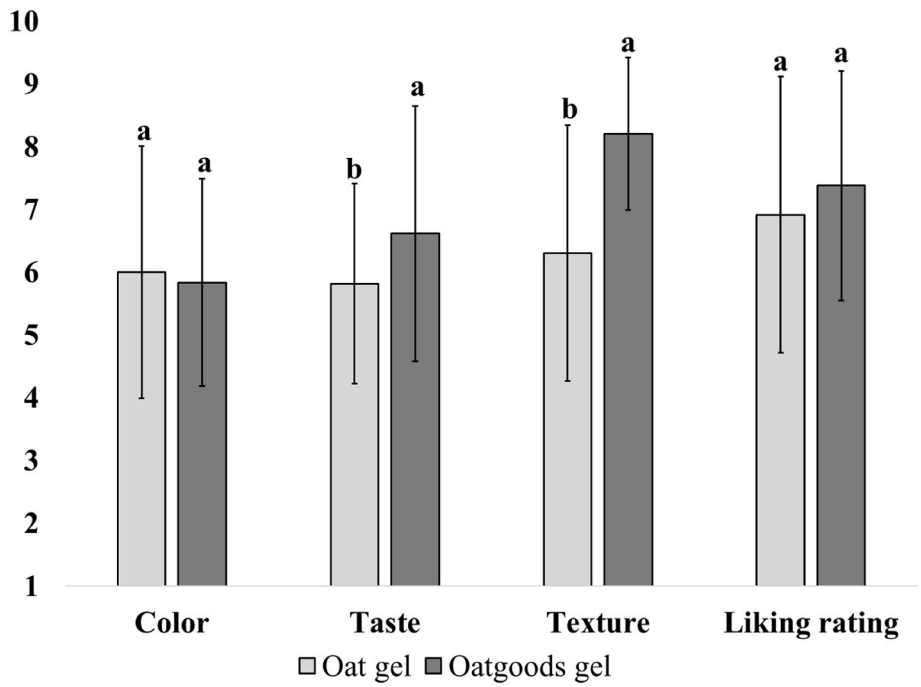

Fig. 4. Hedonic sensory analysis of oat gels (N = 103; Mean ± SEM). Different letters mean significant differences ($P < 0.05$) between samples.

CRediT authorship contribution statement

María Teresa Fernández-Felipe: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Rebeca Fiedorowicz-Bustos:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Noelia Jurado-Chivato:** Validation, Methodology, Investigation, Formal analysis, Data curation. **Andrea García-Cardete:** Methodology, Investigation, Data curation, Conceptualization. **Cristina Mangas-Villa:** Methodology, Investigation, Data curation, Conceptualization. **Manuel Ignacio López-Martínez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2025.118370.

Data availability

No data was used for the research described in the article.

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