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BEYOND CONVENTIONAL CHICKEN MEATBALLS THROUGH OAT FIBER INCORPORATION AND ITS PHYSICOCHEMICAL, TEXTURAL, AND SENSORY EFFECTS

Bianca-Georgiana ANCHIDIN, Mihai-Cătălin CIOBOTARU, Diana-Remina MANOLIU, Adnana-Gabriela SANDU, Ioana GUCIANU, Simona-Mihaela COȘARCĂ, Marius-Mihai CIOBANU, Paul-Corneliu BOIȘTEANU

"Ion Ionescu dela Brad" Iasi University of Life Sciences,
3 Mihail Sadoveanu Alley, 700490, Iasi, Romania

Corresponding author email: marius.ciobanu@iuls.ro

Abstract

Growing interest in clean-label meat products has encouraged the use of dietary fibers that improve nutritional value and technological functionality. Oat fiber was incorporated at 3% and 6% into chicken meatballs from breast and thigh meat, and compared with a control formulation. The samples were evaluated for proximate composition, energy value, pH, water activity, color, Warner–Bratzler cutting properties, texture profile analysis, and sensory perception using hedonic evaluation, descriptive sensory analysis, and PCA. Oat fiber affected most quality parameters. Moisture decreased from 70.96% in the control to 70.05% and 69.50% in the 3% and 6% samples, while dry matter, ash, and fiber increased. Fiber increased from an undetectable level to 2.77% and 5.12%, respectively, whereas protein, fat, energy value, pH, and water activity decreased markedly ($p < 0.001$). Color analysis indicated significant changes in L, b*, and chroma, whereas a* and hue were not significantly affected. Oat fibre addition increased firmness-related parameters, with hardness, Warner-Bratzler shear force, and work of shear rising from 13.52 N, 9.31 N/cm², and 83.24 mJ to 19.29 N, 11.02 N/cm², and 122.55 mJ, respectively; however, springiness and cohesiveness decreased, indicating a firmer but less elastic and less cohesive structure.*

Key words*: chicken meatballs, dietary fiber, meat science, oat fiber, poultry meat products.*

INTRODUCTION

Nutrition is an essential activity that supports human survival. When it comes to resources, a diet based on animal proteins ranks first (Khillare & Kaushal, 2022). Meat and meat products represent a significant part of the human diet, as they contain important nutrients that are difficult to obtain from vegetables and their derivatives (Anchidin et al., 2024; Boișteanu et al., 2023; Boișteanu et al., 2024; Ciobanu et al., 2025; Ianiţchi et al., 2026).

Poultry meat is considered the most consumed meat of animal origin worldwide, recording high consumption rates, particularly in the case of chicken meat (Connolly & Campbell, 2023). Globally, poultry meat consumption has increased dramatically due to changes in trade, the economy, and dietary patterns (Sammani et al., 2025). In this context, it is estimated that by 2034, global poultry meat consumption will reach 173 million tons carcass weight equivalent, representing approximately 62% of the additional growth in global meat consumption (OECD/FAO, 2025). It can be inferred that these results are also due to the absence of cultural or religious restrictions regarding chicken meat, which is one of the most popular products among consumers (Coșarcă et al., 2025).

Demand for ready-to-eat foods, such as canned, frozen, and pre-prepared meals, has increased in the contemporary era due to changes in dietary patterns brought about by urbanization, smaller family units, higher incomes, and the growing number of working women (Hossan et al., 2024). Convenient meat products, which are easy to prepare and consume, are increasingly in demand as a result of rapid urbanization and lifestyle changes, factors that significantly influence consumption habits. Among these products, meatballs are among the most appreciated by consumers (Keerthi et al., 2023). One of the fastest-expanding segments of ready-to-eat meat products on the global market is represented by products such as schnitzels and

nuggets, in which the use of poultry meat accounts for a considerable share. Due to increasing consumption, various ready-to-eat chicken-based products, including chicken wings, marinated chicken breast, meatballs, nuggets, chicken popcorn, and chicken sausages, are increasingly in demand (Khillare & Kaushal, 2022). This orientation toward the use of chicken meat is due to certain characteristics, such as its neutral flavour, consistent and pleasant texture, and light colour. These characteristics make it more suitable for processing compared to other types of meat. They also allow producers to obtain the desired textures and flavour profiles according to market requirements and marketing strategy, as well as the targeted consumer category, such as adults or children (Petracci et al., 2013).

The consumption of meat and meat products consumption is increasing globally as a result of rising incomes and population growth (Flocea et al., 2024; Gucianu et al., 2024). Consumers are demanding healthier meat and meat products, with reduced fat, cholesterol, sodium chloride, and nitrite contents, as well as the addition of various natural ingredients that promote health (Anchidin et al., 2024; Ciobotaru et al., 2024; Manoliu et al., 2023). For this reason, the food industry is reformulating food products to enhance the physiological functionality of natural nutrients or by adding ingredients in order to meet this growing consumer demand (Anchidin et al., 2023; Ciobotaru et al., 2024; Manoliu et al., 2025; Gucianu et al., 2025).

Meat has several physiological functions in the human body and is usually devoid of dietary fibre, which is widely present in plants. According to epidemiological research, the consumption of foods deficient in dietary fibre is one of the main risk factors for the occurrence of numerous lifestyle-related disorders (Manoliu et al., 2024; Mishra et al., 2023). The industry is aware of the need to provide improved food products containing ingredients that support health and prevent nutrition-related disorders (Anchidin et al., 2025; Gucianu et al., 2023; Matei et al., 2024). The addition of substances not usually present in meat, such as dietary fibre, to meat products is a viable way to improve their quality, considering the increased demand for functional and healthy diets (Anchidin et al., 2025; Gucianu, et al., 2024; Ciobanu et al., 2025; Flocea et al., 2025; Manoliu et al., 2025).

The reformulation of meat products through the incorporation of dietary fibres is a well-established research direction in the scientific literature, due to the potential of these ingredients to improve the physicochemical characteristics, textural properties, and sensory acceptability of finished products. The use and incorporation of dietary fibres in meat products are becoming increasingly important. The suitability of dietary fibres for the reformulation of meat products is mainly associated with their functional properties, including water retention, lubrication, reduction of cooking losses, texture modification, and neutral flavour. Dietary fibres obtained from various plant sources, including dehydrated fruits, vegetables, and cereal-derived materials, have been widely used in the food industry and have shown promising technological results (Marczak & Mendes, 2024; Mehta et al., 2015; Mishra et al., 2023; Talukder & Sharma, 2010).

Oat is one of the oldest cereal crops cultivated and consumed worldwide. Its popularity has increased due to its valuable nutritional composition and the multifunctional benefits provided by selected bioactive compounds (Paudel et al., 2021). The technological relevance of oat fibres in meat products is determined by their hydrocolloidal properties, which allow them to function as texturizing agents, partial fat substitutes, and ingredients with a role in improving water- and fat-holding capacity during heat treatment (Piñero et al., 2008). Studies conducted on low-fat beef patties, low-fat burgers, chicken meat patties, and low-fat chicken nuggets have shown that oat fibre, bran, or flour can improve cooking yield, moisture retention, fat retention, water-holding capacity, and emulsion stability, while maintaining acceptable sensory characteristics in reformulated meat products (Piñero et al., 2008; Santhi & Kalaikannan, 2014; Summo et al., 2020; Talukder & Sharma, 2010).

Within meat product reformulation strategies, oat fibres represent a category of plant-based ingredients with significant technological and nutritional value. Interest in their use is mainly associated with the presence of β-glucan, an important component of oat dietary fibre, described as a hydrocolloidal polysaccharide

predominantly located in the soluble fibre fraction and composed of D-glucose monomers (Majumdar et al., 2024; Singla et al., 2024; Summo et al., 2020; Wang & Ellis, 2014).

Therefore, the present study aims to evaluate the effects of incorporating oat fibres on the physicochemical, textural, and sensory characteristics of chicken meatballs made from thigh and breast meat. The proposed approach focuses on obtaining a reformulated product that exploits the technological and nutritional potential of oat fibres by assessing their effects on the physicochemical composition, colour parameters, textural properties, and sensory acceptability of chicken meatballs. Thus, this research contributes to supporting the use of oat fibres as valuable ingredients in the development of chicken meat products with improved technological and nutritional value.

MATERIALS AND METHODS

For this study, three batches of chicken meatballs were manufactured: a control batch without oat fibre addition and two experimental batches formulated with 3% and 6% oat fibre, respectively. The products were prepared using refrigerated chicken meat purchased from METRO Cash & Carry SRL. The chicken meat used for meatball formulation consisted of a standardized mixture of 60% chicken thigh meat and 40% chicken breast meat, and this ratio was maintained constant across all experimental batches. Oat fibre powder was purchased from NO SUGAR SHOP SRL, while the seasoning ingredients, namely salt, garlic powder, sweet paprika, onion powder, dried parsley, black pepper, and ham flavour, were purchased from a local store in Iași, Romania.

The technological process consisted of trimming the chicken meat, mincing it through a 5 mm plate, mixing it with the seasoning ingredients and oat fibre, and manually shaping the composition into meatballs of approximately 40-50 g. Semolina flour was used during shaping to improve handling.

The heat treatment was identical for all batches and included preheating, thermal processing by boiling, drying, and baking, according to the parameters presented in Table 1. After thermal processing, the samples were cooled at 10-12°C for approximately 6h, vacuum-packed, labelled, and stored under refrigeration until laboratory analysis.

Table 1. Thermal treatment parameters applied to chicken meatballs

Technological stage	Time (min)	Chamber temperature (°C)	Core temperature (°C)	Relative humidity (%)
Preheating	10	60	52	80-85
Thermal processing by boiling	-	76	72	99
Drying	10	78	72	10
Baking	60	82	80	40-50

The physicochemical characterization of the chicken meatball samples included the determination of moisture, dry matter, protein, fat, ash, carbohydrates excluding fibre, fibre content, energy value, pH, and water activity. Moisture, protein, fat, and ash contents were determined according to the methods described by (Dinçer et al., 2018). Dietary fibre content was determined according to the method described by Bajcic et al. (2019), previously validated and applied for total dietary fibre determination in meat products. Carbohydrates excluding fibre and energy value were calculated by difference, according to the approach used for proximate composition assessment.

The pH values of the experimental batches were measured using a HI98163 pH meter equipped with an FC2323 electrode (SC Hanna Instruments SRL). Due to the blade-shaped tip of the electrode, measurements were performed by direct insertion into the meat samples.

Water activity (aw) was determined with an AquaLab 4TE instrument (Addium Inc., Washington, DC, USA) after sample homogenization by grinding.

The instrumental colour of the chicken meatball samples was determined using a Konica Minolta CR-410 colorimeter (Konica Minolta, Inc., Tokyo, Japan), under a D65 illuminant and a 10° standard observer. The results were expressed in the CIELAB colour space as lightness (L*), redness (a*), and yellowness (b*). Based on these coordinates, chroma (C*) and hue angle (h°) were calculated according to the equations

reported by Sen et al. (2014), while the total colour difference (ΔE) was calculated according to (Tkacz et al., 2020).

Texture analysis was performed using a TA1+1K Plus texturometer (Ametek, Inc., USA). Before analysis, the samples were cut into standardized shapes depending on the test performed. For Texture Profile Analysis (TPA), cylindrical samples measuring 2.5 cm in height and approximately 2.0 cm in diameter were used for the double-compression test. For Warner-Bratzler shear force determination, parallelepiped samples measuring approximately 5.0 × 1.5 cm were prepared and sheared using a Warner-Bratzler V-shaped notch blade.

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

$$\text{Hue angle (h*)} = tan^{-1} \times b^*/a^* \quad (2)$$

$$\Delta E^* = [(\Delta a^*)^2 + (\Delta b^*)^2 + (\Delta L^*)^2]^{0.5} \quad (3)$$

The sensory evaluation included hedonic analysis and quantitative descriptive analysis. Descriptive analysis was used because it allows the sensory profile of food products to be quantified through relevant attributes evaluated by trained assessors, while hedonic analysis provides information on product acceptability (Mongi & Gomezulu, 2022; Ruiz-Capillas et al., 2021). Principal component analysis (PCA) was subsequently applied to the descriptive sensory data, as this multivariate method is useful for reducing complex sensory datasets and identifying the main attributes responsible for differentiating the samples (Chapman et al., 2001).

Sensory analysis is an important method for assessing the perceived quality and acceptability of food products. Sensory characterization is used to obtain a complete qualitative and quantitative description of the sensory attributes of a product (Boișteanu et al., 2025). For centuries, this type of analysis has been used to approve or reject food products (Ciobanu et al., 2023).

In the present study, sensory evaluation was performed by a panel of 44 semi-trained assessors, consisting of 32 females and 12 males, aged between 20 and 22 years. Prior to the evaluation, the assessors were familiarized with the sensory descriptors and the evaluation procedure in order to ensure a common understanding of the attributes assessed. The descriptors “smoky odor” and “smoked taste” were included in the sensory profile to describe smoked/ham-like aromatic notes derived from the ham flavour used in the seasoning mixture, as the products were not subjected to a smoking process. Moreover, the baking stage applied during thermal treatment may have slightly enhanced the perception of these aroma notes, making them more detectable by the assessors. The sensory evaluation was performed in a specialized sensory analysis laboratory of IULS, under controlled environmental conditions. The samples were coded with random three-digit numbers and presented to the assessors in a randomized order to minimize order and expectation effects. A 5-minute break was provided between samples in order to reduce sensory fatigue and carry-over effects. During this interval, the assessors were provided with water and bread for palate cleansing and for neutralizing residual tastes before evaluating the next sample. The sensory session was conducted in accordance with the ethical principles of the Declaration of Helsinki. Participation was voluntary, and all assessors were informed about the purpose of the study and the nature of the samples before evaluation.

Statistical analysis was performed using XLSTAT software (Lumivero, Denver, CO, USA). Three experimental batches were analysed: CBO-0, CBO-3, and CBO-6. For each batch, all physicochemical determinations were performed in five analytical replicates (n = 5), except for colour measurements, which were carried out in ten analytical replicates (n = 10). The experimental data were processed to determine the mean values and standard deviations of the analysed parameters, and the results were expressed as mean ± standard deviation.

The significance of differences between batches was assessed using one-way analysis of variance (ANOVA), followed by Tukey’s post hoc test for multiple comparisons and Dunnett’s test for comparison of the experimental batches with the control batch, where appropriate. Statistical significance was considered at $p < 0.05$. Principal component analysis (PCA) was also

performed using XLSTAT to visualize the relationships between the experimental batches and the analysed variables.

RESULTS AND DISCUSSIONS

Effect of oat fibre addition on the physico-chemical properties of chicken meatballs

The nutritional composition of the oat fibre powder used in the formulation is presented in Table 2.

Table 2. Nutritional composition of oat fibre powder

Nutritional parameter of oat fiber powder	Value / 100 g
Fat	0.2 g
Carbohydrates	0.1 g
Dietary fibre	93.0 g
Protein	0.4 g
Salt	0.10 g

Values are expressed per 100 g of oat fibre powder

According to the product label, the ingredient was characterized by a very high dietary fibre content, representing 93.0 g/100 g, while the contents of carbohydrates, protein, fat and salt were very low, with values of 0.1, 0.4, 0.2 and 0.10 g/100 g, respectively. This composition indicates that the ingredient mainly contributed to the dietary fibre fraction of the chicken meatball formulations, with minimal direct contribution to available carbohydrates, protein or lipid content.

The physicochemical results in Table 3 show a clear reformulation effect induced by oat fibre addition. Moisture decreased significantly from 70.96 ± 0.09^{a} in CBO-0 to 70.05 ± 0.30^{b} in CBO-3 and 69.50 ± 0.30^{c} in CBO-6 (global $p < 0.0001$; Dunnett CBO-0 vs. CBO-3: $p = 0.000$; CBO-0 vs. CBO-6: $p < 0.0001$), while dry matter increased in the opposite direction from 29.04 ± 0.09^{c} to 29.95 ± 0.30^{b} and 30.50 ± 0.30^{a} under the same significance pattern. The decrease in moisture content observed in oat fibre-supplemented samples may be associated with the increased dry matter fraction introduced by the fibre ingredient. A similar trend was reported by Yılmaz (2005), who observed a progressive reduction in moisture content in low-fat meatballs as wheat bran concentration increased from 5% to 20%.

Protein and fat also decreased progressively, from 19.80 ± 0.02^{a} to 18.35 ± 0.08^{b} and 17.05 ± 0.08^{c} for protein, and from 7.56 ± 0.02^{a} to 7.00 ± 0.06^{b} and 6.35 ± 0.06^{c} for fat, with global $p < 0.0001$ and extremely significant Dunnett comparisons for both supplemented samples ($p < 0.001$). This trend is consistent with the low protein and fat contribution of the oat fibre powder and reflects the partial replacement of the meat matrix.

Table 3. Physicochemical characteristics of chicken meatball samples supplemented with oat fibre

Parameter	CBO-0	CBO-3	CBO-6	Global *p*-value	Dunnett CBO-0 vs. CBO-3	Dunnett CBO-0 vs. CBO-6
Moisture (%)	70.96 ± 0.09^{a}	70.05 ± 0.30^{b}	69.50 ± 0.30^{c}	**<0.0001*** **	**0.000*** **	**<0.0001*** **
Dry matter (%)	29.04 ± 0.09^{c}	29.95 ± 0.30^{b}	30.50 ± 0.30^{a}	**<0.0001*** **	**0.000*** **	**<0.0001*** **
Protein (%)	19.80 ± 0.02^{a}	18.35 ± 0.08^{b}	17.05 ± 0.08^{c}	**<0.0001*** **	**<0.0001*** **	**<0.0001*** **
Fat (%)	7.56 ± 0.02^{a}	7.00 ± 0.06^{b}	6.35 ± 0.06^{c}	**<0.0001*** **	**<0.0001*** **	**<0.0001*** **
Ash (%)	1.60 ± 0.02^{c}	1.68 ± 0.05^{b}	1.87 ± 0.05^{a}	**<0.0001*** **	**0.015***	**<0.0001*** **
Carbohydrates, excluding fibre **(%)**	0.08 ± 0.03^{b}	0.15 ± 0.03^{a}	0.11 ± 0.03^{ab}	**0.014***	**0.008****	0.266^{ns}
Fibre (%)	–	2.77 ± 0.08^{b}	5.12 ± 0.08^{a}	**<0.0001*** **	**<0.0001*** **	**<0.0001*** **
Energy value (kcal/100 g)	147.56 ± 0.36^{a}	142.54 ± 1.17^{b}	136.03 ± 1.17^{c}	**<0.0001*** **	**<0.0001*** **	**<0.0001*** **
Energy value (kJ/100 g)	617.35 ± 1.50^{a}	596.39 ± 4.89^{b}	569.15 ± 4.90^{c}	**<0.0001*** **	**<0.0001*** **	**<0.0001*** **
pH	6.52 ± 0.05^{a}	6.19 ± 0.01^{b}	6.12 ± 0.05^{c}	**<0.0001*** **	**<0.0001*** **	**<0.0001*** **
Water activity (a_w)	0.950 ± 0.001^{a}	0.936 ± 0.002^{b}	0.930 ± 0.001^{c}	**<0.0001*** **	**<0.0001*** **	**<0.0001*** **

Values are expressed as mean ± SD. Different superscript letters in the same row indicate significant differences among samples ($p < 0.05$). CBO-0, control; CBO-3, sample with 3% oat fibre; CBO-6, sample with 6% oat fibre. Carbohydrates were calculated by difference and exclude dietary fibre. Global *p*-value indicates the overall effect of oat fibre addition, while Dunnett comparisons show differences between the control and supplemented samples. ns, not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Ash content increased from 1.60 ± 0.02^{c} to 1.68 ± 0.05^{b} and 1.87 ± 0.05^{a} (global $p < 0.0001$; Dunnett: $p = 0.015$ and $p < 0.0001$), while carbohydrates excluding fibre remained very low, as expected from the ingredient label: 0.08 ± 0.03^{b}, 0.15 ± 0.03^{a}, and 0.11 ± 0.03^{ab} (global *p*

= 0.014; Dunnett: p = 0.008 and p = 0.266). Fibre increased markedly from an undetectable level in CBO-0 to 2.77 ± 0.08^{b} in CBO-3 and 5.12 ± 0.08^{a} in CBO-6 (global p < 0.0001; Dunnett p < 0.0001 for both comparisons), confirming that oat fibre was the main driver of nutritional differentiation. Energy value decreased significantly from 147.56 ± 0.36^{a} kcal/100 g to 142.54 ± 1.17^{b} and 136.03 ± 1.17^{c} kcal/100 g (global p < 0.0001; Dunnett p < 0.0001), reflecting the replacement of energy-dense meat constituents by fibre. Similar decreasing patterns were observed for pH (6.52 ± 0.05^{a}, 6.19 ± 0.01^{b}, 6.12 ± 0.05^{c}) and water activity (0.950 ± 0.001^{a}, 0.936 ± 0.002^{b}, 0.930 ± 0.001^{c}), both with global p < 0.0001 and significant Dunnett comparisons.

These findings agree with previous studies on fibre-enriched poultry products. Santhi & Kalaikannan (2014) reported that oat flour addition in low-fat chicken nuggets significantly increased crude fibre, while reducing crude protein and fat, which supports the dilution pattern observed in the present study.

Overall, these results indicate that oat fibre incorporation effectively improved the fibre profile of chicken meatballs while inducing predictable compositional changes, mainly through reduced moisture, protein, fat, pH and water activity, and increased dry matter, ash and dietary fibre contents.

Table 4 displays the instrumental colour parameters of the chicken meatball samples that were treated with varying amounts of oat fibre. Significant changes were mostly observed in brightness, yellowness, and chroma when oat fibre was added (p < 0.05). From 59.93 ± 0.90^{b} in the control sample to 60.81 ± 0.76^{ab} in CBO-3 and 61.03 ± 1.22^{a} in CBO-6, the L* value increased slightly. Despite the modest numerical increase, the global p-value (p = 0.044) showed that the addition of oat fibre had a significant impact. Only the difference between CBO-0 and CBO-6 was significant, according to Dunnett's test (p = 0.034); CBO-3 did not differ substantially from the control (p = 0.100). This pattern was validated by Tukey's test, which classified CBO-3 as an intermediate group.

The redness parameter, a*, was not significantly affected by the formulation, with values ranging from 7.70 ± 1.67^{a} in CBO-0 to 8.00 ± 1.21^{a} in CBO-6. This was confirmed by the global p-value (p = 0.899), by the non-significant Dunnett comparisons for CBO-3 (p = 0.931) and CBO-6 (p = 0.864), and by the identical Tukey superscript letters assigned to all samples. In contrast, b* increased significantly from 17.51 ± 1.84^{b} in CBO-0 to 19.32 ± 0.95^{a} in CBO-3 and 19.57 ± 1.11^{a} in CBO-6. The global effect was significant (p = 0.004), and both Dunnett comparisons confirmed significant differences from the control sample (p = 0.011 for CBO-3 and p = 0.004 for CBO-6). A similar pattern was observed for chroma, which increased from 19.22 ± 1.45^{b} in CBO-0 to 20.93 ± 0.92^{a} in CBO-3 and 21.18 ± 0.88^{a} in CBO-6, with a significant global effect (p = 0.001) and significant Dunnett comparisons for both supplemented samples (p = 0.004 and p = 0.001, respectively).

Table 4. Instrumental colour characteristics of chicken meatball samples supplemented with different levels of oat fibre

Colour parameter	Samples			Global p-value	Dunnett CBO-0 vs. CBO-3	Dunnett CBO-0 vs. CBO-6
	CBO-0	CBO-3	CBO-6			
L*(D65)	59.93 ± 0.90^{b}	60.81 ± 0.76^{ab}	61.03 ± 1.22^{a}	**0.044***	0.100^{ns}	**0.034***
a*(D65)	7.70 ± 1.67^{a}	7.91 ± 1.58^{a}	8.00 ± 1.21^{a}	0.899^{ns}	0.931^{ns}	0.864^{ns}
b*(D65)	17.51 ± 1.84^{b}	19.32 ± 0.95^{a}	19.57 ± 1.11^{a}	**0.004****	**0.011***	**0.004****
Croma (C*)	19.22 ± 1.45^{b}	20.93 ± 0.92^{a}	21.18 ± 0.88^{a}	**0.001*****	**0.004****	**0.001*****
Hue angle (rad)	1.15 ± 0.11^{a}	1.18 ± 0.08^{a}	1.18 ± 0.07^{a}	0.691^{ns}	0.667^{ns}	0.686^{ns}
ΔE	—	3.47 ± 1.27^{a}	4.26 ± 1.34^{a}	0.191^{ns}	-	-

Values are expressed as mean ± standard deviation. CBO-0 = control sample without oat fibre; CBO-3 = sample supplemented with 3% oat fibre; CBO-6 = sample supplemented with 6% oat fibre. Different superscript letters within the same row indicate significant differences according to Tukey's HSD test (p < 0.05). Global p-value indicates the overall effect of oat fibre addition, while Dunnett comparisons show differences between the control and supplemented samples. ns = not significant; *, ** and *** indicate significance at p < 0.05, p < 0.01 and p < 0.001, respectively.

The addition of oat fibre did not significantly affect hue angle (rad) because the values for CBO-0, CBO-3, and CBO-6 were 1.15 ± 0.11^{a}, 1.18 ± 0.08^{a}, and 1.18 ± 0.07^{a}, respectively. The non-significant Dunnett comparisons, the global p-value (p = 0.691), and the identical Tukey

letter for every sample supported this finding. The total colour difference, ΔE, increased from 3.47 ± 1.27^{a} in CBO-3 to 4.26 ± 1.34^{a} in CBO-6. However, this difference was not statistically significant ($p = 0.191$), suggesting that the supplemented samples' overall colour variation was not significantly affected by the increase in oat fibre level from 3% to 6%.

Taken together, the findings show that while redness and hue angle remained unchanged, the inclusion of oat fibre mostly enhanced the chicken meatballs' lightness, yellowness, and colour intensity. These results are in line with earlier research demonstrating that adding dietary fibre to meat products might alter their instrumental colour characteristics. (Kilincceker & Yilmaz, 2019) found that the inclusion of fibre changed the L*, a*, and b* values in chicken meatballs, while Gore et al. (2022) found that the naturally yellowish tint of oat fibre boosted the yellowness of meat sausages.

Table 5 displays the chicken meatball samples' instrumental texture parameters. Almost every textural feature was significantly affected by the inclusion of oat fibre ($p < 0.05$). With a highly significant global effect ($p < 0.0001$), Warner-Bratzler shear force increased gradually from 9.31 ± 0.52^{c} in CBO-0 to 10.05 ± 0.27^{b} in CBO-3 and 11.02 ± 0.15^{a} in CBO-6. Tukey's test separated all samples into distinct groups, whereas Dunnett's test verified substantial differences between the control and both supplemented samples ($p = 0.010$ for CBO-3 and $p < 0.0001$ for CBO-6). Work of shear showed a similar increasing trend, rising from 83.24 ± 3.00^{c} to 101.03 ± 4.49^{b} and 122.55 ± 3.20^{a} ($p < 0.0001$), suggesting that the inclusion of oat fibre enhanced the product's mechanical resistance.

The TPA parameters showed the same tendency for hardness, which increased significantly from 13.52 ± 0.76^{c} in CBO-0 to 16.13 ± 1.18^{b} in CBO-3 and 19.29 ± 1.02^{a} in CBO-6 ($p < 0.0001$). Dunnett comparisons were significant for both fibre-supplemented samples ($p < 0.05$), and Tukey's test confirmed a clear separation among the three formulations. This increase may be related to the higher dry matter and fibre contents observed in the physicochemical results Table 3, together with the reduction in moisture and fat, which can contribute to a firmer and more compact meat matrix. A comparable effect was reported by Souza et al. (2019) in low-fat cooked sausages, where oat fibre increased hardness, especially at higher concentrations; similarly, Gore et al. (2022) reported that sausages with oat fibre showed good gel strength and a compact microstructure. Adhesiveness values became progressively more negative with oat fibre addition, changing from -4.11 ± 0.04 mJ in CBO-0 to -4.90 ± 0.12 mJ in CBO-3 and -5.21 ± 0.06 mJ in CBO-6, with extremely significant global and Dunnett effects ($p < 0.0001$). Since adhesiveness in TPA is expressed as the negative work required to detach the sample from the probe, the increase in the absolute value indicates higher adhesive work in the oat fibre-supplemented samples. A similar trend was reported by Dhanasekar & Kalaikannan (2014) in low-fat chicken nuggets supplemented with oat flour, where increasing oat flour levels significantly increased hardness and adhesiveness, while cohesiveness, springiness, and resilience decreased. Therefore, the present results are consistent with previous findings showing that oat-derived fibre ingredients can promote a firmer and more adhesive meat matrix, while reducing elasticity and internal cohesion.

Additionally, springiness markedly decreased from 0.70 ± 0.02^{a} to 0.59 ± 0.03^{b} and 0.50 ± 0.04^{c} ($p < 0.0001$), indicating a decrease in elasticity in the fibre-enriched samples. Cohesiveness decreased slightly but significantly from 0.40 ± 0.02^{a} in CBO-0 to 0.38 ± 0.02^{ab} in CBO-3 and 0.35 ± 0.02^{b} in CBO-6 ($p = 0.003$). Only CBO-6 showed a substantial decrease ($p = 0.001$), according to Dunnett's test, although CBO-3 continued to be statistically comparable to the control ($p = 0.081$).

Gumminess increased from 5.46 ± 0.23^{b} to 6.07 ± 0.52^{ab} and 6.70 ± 0.38^{a} ($p = 0.001$), with only CBO-6 showing a significant Dunnett difference ($p = 0.001$). On the other hand, chewiness dropped from 3.84 ± 0.23^{a} in CBO-0 to 3.56 ± 0.29^{ab} in CBO-3 and 3.37 ± 0.20^{b} in CBO-6 ($p = 0.029$). Dunnett's test only revealed a significant difference between CBO-0 and CBO-6 ($p = 0.018$). This decrease can be explained by the reduction in springiness and cohesiveness, since chewiness is calculated from hardness, cohesiveness and springiness. The findings indicate that oat fibre improved the firmness and shear resistance of chicken meatballs, but at greater concentrations, it decreased their cohesion, elasticity, and chewiness.

Table 5. Warner-Bratzler and texture profile analysis parameters of oat fibre-supplemented chicken meatball samples

Texture test	Texture parameter	Samples			Global *p*-value	Dunnett CBO-0 vs. CBO-3	Dunnett CBO-0 vs. CBO-6
		CBO-0	CBO-3	CBO-6			
Warner–Bratzler	Shear force, N/cm^2	9.31 ± 0.52^c	10.05 ± 0.27^b	11.02 ± 0.15^a	**<0.0001*** **	**0.010** **	**<0.0001*** **
	Work of shear, mJ	83.24 ± 3.00^c	101.03 ± 4.49^b	122.55 ± 3.20^a	**<0.0001*** **	**<0.0001*** **	**<0.0001*** **
Texture Profile Analysis (TPA)	Hardness, N	13.52 ± 0.76^c	16.13 ± 1.18^b	19.29 ± 1.02^a	**<0.0001*** **	**0.003** **	**<0.0001*** **
	Adhesiveness, mJ	-4.11 ± 0.04^a	-4.90 ± 0.12^b	-5.21 ± 0.06^c	**<0.0001*** **	**<0.0001*** **	**<0.0001*** **
	Springiness, -	0.70 ± 0.02^a	0.59 ± 0.03^b	0.50 ± 0.04^c	**<0.0001*** **	**0.000*** **	**<0.0001*** **
	Cohesiveness, -	0.40 ± 0.02^a	0.38 ± 0.02^{ab}	0.35 ± 0.02^b	**0.003** **	0.081^{ns}	**0.001*** **
	Gumminess, N	5.46 ± 0.23^b	6.07 ± 0.52^{ab}	6.70 ± 0.38^a	**0.001*** **	0.056^{ns}	**0.001*** **
	Chewiness, N	3.84 ± 0.23^a	3.56 ± 0.29^{ab}	3.37 ± 0.20^b	**0.029***	0.157^{ns}	**0.018***

Values are expressed as mean ± standard deviation. CBO-0 = control sample without oat fibre; CBO-3 = sample supplemented with 3% oat fibre; CBO-6 = sample supplemented with 6% oat fibre. Different superscript letters within the same row indicate significant differences according to Tukey's HSD test ($p < 0.05$). Global *p*-value indicates the overall effect of oat fibre addition, while Dunnett comparisons show differences between the control and supplemented samples. ns = not significant; *, ** and *** indicate significance at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

Sensory profile and acceptability of chicken meatballs with oat fibre addition

Figure 1 shows the hedonic evaluation of chicken meatball samples that have been supplemented with oat fibre. Regardless of the amount of oat fibre, all samples obtained high scores overall, typically above 7.5, suggesting good consumer acceptability. The control sample, CBO-0, showed slightly higher scores for appearance, odour, texture and overall acceptability, suggesting that the traditional formulation was marginally preferred by the assessors.

The hedonic profile was slightly affected by the addition of oat fibre. Particularly in terms of look, aroma, and general acceptability, CBO-3 kept values extremely near to the control sample, suggesting that the addition of 3% oat fibre had no detrimental effects on consumer perception. CBO-6, on the other hand, had slightly lower ratings for appearance, aroma, texture, and overall acceptability. This could be related to the increased fibre content and how it affects the structure and sensory perception of the food.

The oat fibre-supplemented samples' taste was either slightly better than or equal to that of the control, suggesting that the addition of fibre did not negatively affect flavour perception. This finding is significant since adding dietary fibre to meat products might occasionally change their texture, taste intensity, or juiciness. Overall, the hedonic evaluation indicates that chicken meatballs supplemented with oat fibre were still well-liked, with CBO-3 emerging as the most balanced formulation because it improved the nutritional profile by adding fibre while maintaining a sensory profile similar to the control.

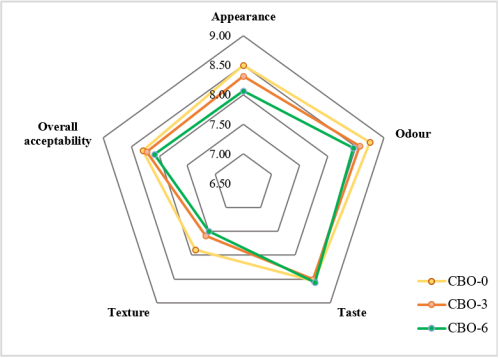


Figure 1. Hedonic evaluation of chicken meatball samples supplemented with different levels of oat fibre

Table 6 displays the descriptive sensory profile of oat fibre-supplemented chicken meatball samples. Most texture parameters were not significantly affected ($p > 0.05$), while significant differences were observed mainly in appearance-, odour-, and taste-related descriptors ($p < 0.05$). Compared to CBO-0 (7.59 ± 0.26^a) and CBO-3 (7.45 ± 0.28^a), the light pinkish-cream appearance score of CBO-6 (6.20 ± 0.39^b) was significantly lower ($p = 0.004$), suggesting that the highest oat fibre level altered the product's visual perception. Furthermore, the score for spherical shape with slight irregularities gradually decreased from 7.95 ± 0.15^a in CBO-0 to 6.84 ± 0.29^b in CBO-3 and 6.52 ± 0.38^c in CBO-6 ($p < 0.0001$). The homogeneous fat distribution decreased in the fibre-supplemented samples ($p = 0.000$), while the slightly dry, flaky aspect increased considerably in CBO-6 (2.95 ± 0.32^a) compared to the control (1.95 ± 0.22^b) ($p = 0.034$).

Table 6. Descriptive sensory profile of oat fibre-supplemented chicken meatball samples

Sensory characteristic	CBO-0	CBO-3	CBO-6	*p*-value
Ingredients evenly dispersed	7.12 ± 0.34^{a}	6.55 ± 0.35^{a}	6.18 ± 0.35^{a}	0.102^{ns}
Even color	6.36 ± 0.41^{a}	6.50 ± 0.36^{a}	6.48 ± 0.38^{a}	0.783^{ns}
Light pinkish-cream appearance	7.59 ± 0.26^{a}	7.45 ± 0.28^{a}	6.20 ± 0.39^{b}	**0.004****
Firm, dense structure	6.42 ± 0.37^{a}	6.61 ± 0.35^{a}	6.75 ± 0.35^{a}	0.943^{ns}
Perceptible connective tissue	3.15 ± 0.27^{a}	2.80 ± 0.32^{a}	3.02 ± 0.31^{a}	0.598^{ns}
Generally spherical with minor irregularities	7.95 ± 0.15^{a}	6.84 ± 0.29^{b}	6.52 ± 0.38^{c}	**<0.0001*****
Heterogeneous visual pattern	7.20 ± 0.31^{a}	7.05 ± 0.30^{a}	7.18 ± 0.30^{a}	0.889^{ns}
Slightly dry, flaky aspect	1.95 ± 0.22^{b}	2.73 ± 0.29^{b}	2.95 ± 0.32^{a}	**0.034***
Uniform fat distribution	7.11 ± 0.27^{a}	5.77 ± 0.41^{b}	6.23 ± 0.39^{b}	**0.000*****
Smoky odor	5.05 ± 0.42^{a}	3.84 ± 0.38^{b}	3.77 ± 0.37^{b}	**0.002****
Cooked meat odor	8.36 ± 0.29^{ab}	8.50 ± 0.19^{a}	7.23 ± 0.32^{b}	**0.004****
Odor typical of the product category	8.78 ± 0.06^{a}	8.25 ± 0.21^{a}	7.48 ± 0.31^{b}	**<0.0001*****
Faint odor intensity	1.86 ± 0.15^{b}	2.20 ± 0.26^{b}	4.07 ± 0.37^{a}	**<0.0001*****
Faint rancid odor	1.16 ± 0.07^{b}	1.39 ± 0.15^{ab}	1.66 ± 0.19^{a}	**0.042***
Aroma profile characteristic of commercial products	8.36 ± 0.19^{a}	8.11 ± 0.24^{a}	6.61 ± 0.31^{b}	**<0.0001*****
Taste of spices	5.16 ± 0.42^{a}	4.66 ± 0.35^{a}	5.02 ± 0.45^{a}	0.630^{ns}
Smoked taste	4.09 ± 0.39^{a}	3.95 ± 0.39^{a}	4.11 ± 0.33^{a}	0.955^{ns}
Well-balanced meat-seasoning taste	7.36 ± 0.31^{a}	6.48 ± 0.39^{a}	6.73 ± 0.36^{a}	0.148^{ns}
Pleasant flavor persistence	6.70 ± 0.37^{a}	6.55 ± 0.33^{a}	6.41 ± 0.39^{a}	0.888^{ns}
Perceptible aftertaste	6.14 ± 0.37^{a}	6.00 ± 0.35^{a}	5.84 ± 0.35^{a}	0.772^{ns}
Pronounced meat taste	8.42 ± 0.15^{a}	6.95 ± 0.39^{b}	6.66 ± 0.35^{b}	**0.000*****
Salty taste	4.80 ± 0.36^{a}	4.50 ± 0.34^{a}	4.45 ± 0.38^{a}	0.742^{ns}
Vegetal taste	2.32 ± 0.28^{b}	4.05 ± 0.38^{a}	4.25 ± 0.37^{a}	**<0.0001*****
Umami taste	4.74 ± 0.36^{a}	4.20 ± 0.38^{a}	4.05 ± 0.36^{a}	0.652^{ns}
Undesirable taste	1.13 ± 0.13^{a}	1.66 ± 0.19^{a}	1.73 ± 0.20^{a}	0.095^{ns}
Firm texture	5.98 ± 0.38^{a}	5.84 ± 0.40^{a}	6.20 ± 0.40^{a}	0.804^{ns}
Elastic texture	4.54 ± 0.37^{a}	4.84 ± 0.40^{a}	5.59 ± 0.37^{a}	0.141^{ns}
Adhesive texture	4.15 ± 0.36^{a}	3.61 ± 0.34^{a}	3.50 ± 0.37^{a}	0.790^{ns}
Well-bound texture	5.78 ± 0.32^{a}	6.02 ± 0.41^{a}	6.11 ± 0.37^{a}	0.974^{ns}
Friable texture	4.06 ± 0.30^{a}	3.41 ± 0.36^{a}	3.05 ± 0.33^{a}	0.465^{ns}
Structural integrity during mastication	6.02 ± 0.32^{a}	5.91 ± 0.36^{a}	6.20 ± 0.37^{a}	0.436^{ns}

Values are expressed as mean ± standard deviation. CBO-0 = control sample without oat fibre; CBO-3 = sample supplemented with 3% oat fibre; CBO-6 = sample supplemented with 6% oat fibre. Different superscript letters within the same row indicate significant differences according to Tukey's HSD test ($p < 0.05$). ns = not significant; *, ** and *** indicate significance at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

In terms of odour descriptors, the addition of oat fibre decreased the smoky odour from 5.05 ± 0.42^{a} in CBO-0 to 3.84 ± 0.38^{b} in CBO-3 and 3.77 ± 0.37^{b} in CBO-6 ($p = 0.002$). The odour profile typical of commercial products and the odour typical of the product category were also lower in CBO-6; however, the intensity of the faint odour increased significantly from 1.86 ± 0.15^{b} in CBO-0 to 4.07 ± 0.37^{a} in CBO-6 ($p < 0.0001$). The faint rancid odour also showed a slight but significant increase ($p = 0.042$), even though the absolute values remained low.

The most significant changes in taste characteristics were observed for pronounced meat taste and vegetal taste. While vegetal taste increased from 2.32 ± 0.28^{b} in the control to 4.05 ± 0.38^{a} and 4.25 ± 0.37^{a} in the oat fibre-supplemented samples ($p < 0.0001$), pronounced meat taste decreased from 8.42 ± 0.15^{a} in CBO-0 to 6.95 ± 0.39^{b} in CBO-3 and 6.66 ± 0.35^{b} in CBO-6 ($p < 0.001$). These findings suggest that the addition of oat fibre shifted the sensory perception from a strongly meat-associated profile towards a slightly more vegetal profile.

The current findings are consistent with those of Verma & Banerjee (2010), who noted that oat bran can maintain the inherent aromatic constituents of meat, mimic fat, increase mouthfeel, and lack a strong cereal flavour. These characteristics could help to explain why, especially at the 3% addition level, the oat fiber-supplemented samples retained good overall sensory acceptance. However, the decrease in strong meat flavour and smokey odour and the increase in vegetable flavour at higher fibre levels suggest that adding too much oat fibre may slightly change the typical meat sensory profile, causing perception to shift towards more vegetal overtones.

In general, Tukey's test revealed that the 6% oat fibre formulation was generally associated with the most pronounced sensory changes, whereas CBO-3 often remained closest to the control. Similar effects have been documented in meat

products supplemented with fibre, where the type and concentration of dietary fibre added affected sensory attributes related to colour, flavour, and texture. While Szczepaniak et al. (2005) found that oat fibre altered colour uniformity and decreased fatty aroma and taste intensity in finely comminuted sausages, Kilincceker & Yilmaz (2019) reported that fibre concentration affected the sensory qualities of chicken meatballs, with the highest acceptable level depending on the fibre source.

The PCA biplot presented in Figure 2 explains 100% of the total variability, with F1 accounting for 73.66% and F2 for 26.34%. The angle between the vectors indicates the relationships among sensory descriptors: variables oriented in a similar direction are positively correlated, variables positioned in opposite directions are negatively correlated, while approximately perpendicular vectors indicate weak or no correlation.

The position of CBO-0 indicates a close association with descriptors such as pronounced meat taste, salty taste, umami taste, adhesive texture, friable texture, ingredients evenly dispersed, pleasant flavor persistence, odour typical of the product category and aroma profile characteristic of commercial products. The small angles between these vectors suggest that these descriptors were positively correlated and contributed similarly to the sensory characterization of the control sample.

CBO-6 was located closer to descriptors such as faint odour intensity, faint rancid odour, elastic texture, firm, dense structure, firm texture and structural integrity during mastication. The similar orientation of these vectors indicates a relationship among these attributes and shows that they contributed together to the differentiation of the CBO-6 formulation. CBO-3 was positioned closer to vegetal taste, undesirable taste and even color, suggesting a stronger association with these descriptors.

Descriptors oriented in similar directions, such as pronounced meat taste, salty taste and umami taste, indicate close correlations, while descriptors placed in opposite directions, such as pronounced meat taste and vegetal taste, suggest contrasting sensory tendencies. Overall, the PCA shows that each formulation was associated with a distinct group of sensory descriptors, with CBO-0 linked mainly to meat- and aroma-related attributes, CBO-6 to texture- and faint odour-related descriptors, while CBO-3 occupied an intermediate position, suggesting a transitional sensory profile between the control and the highest oat fibre level.

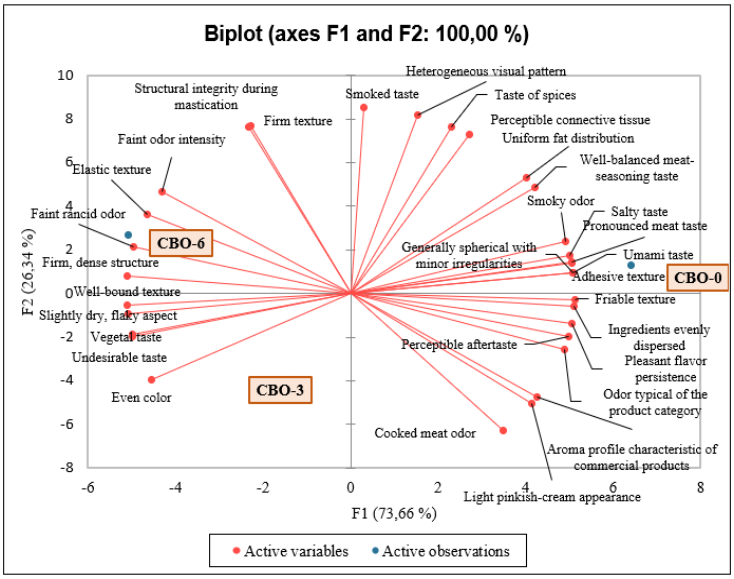


Figure 2. Principal component analysis (PCA) biplot of the sensory descriptors and chicken meatball samples supplemented with oat fibre

CONCLUSIONS

Chicken meatball samples showed distinct compositional, instrumental, and sensory alterations following the addition of oat fibre. As anticipated, the addition of oat fibre reduced moisture, protein, fat, energy value, pH, and water activity, while increasing dietary fibre content and dry matter. These modifications, primarily resulting from the substitution of a high-fibre, low-fat, and low-protein ingredient and the partial replacement of the meat matrix, confirm the reformulation effect of oat fibre.

The physicochemical changes were closely linked to the instrumental texture results. Higher shear force, work of shear, and hardness were associated with decreased moisture and fat contents, as well as increased dry matter and fibre content. This suggests the formation of a more robust and mechanically resistant product structure. Simultaneously, the decrease in chewiness, cohesiveness, and springiness, particularly in CBO-6, indicates that although firmness increased, a higher oat fibre content made the structure less cohesive and elastic.

The sensory evaluation largely mirrored the instrumental results. The increase in L*, b*, and chroma was in line with the changes seen in visual descriptors, particularly in CBO-6, where the greater dry/flaky aspect and lower score for light pinkish-cream look suggested that colour alterations were noticeable at the sensory level. Similarly, the PCA connection of CBO-6 with firm texture, solid and dense structure, and structural integrity during mastication was associated with increases in instrumental hardness, shear force, and work of shear. The reduction in cohesiveness and springiness, however, implies that the stiffer structure brought about by oat fibre was not always linked to greater elasticity or internal cohesiveness.

From a sensory standpoint, oat fibre mainly affected appearance-, taste-, and odour-related descriptors. While CBO-6 was more strongly associated with vegetal flavour, faint rotten odour, and faint odour intensity, CBO-0 was associated with meat-related and product-typical characteristics. CBO-3 exhibited an intermediate behaviour, retaining a profile more similar to the control. Overall, the findings suggest that oat fibre can enhance the nutritional profile of chicken meatballs; however, in terms of colour, texture, and sensory perception, the 3% level appears to be the most balanced formulation.

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