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The effect of thermal processing on the nutritional value of pork meat

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Abstract

The method of thermal processing significantly affects the nutritional value and chemical composition of pork. This study aimed to evaluate the impact of various cooking techniques (boiling, roasting, grilling, sous-vide) and determine which method is most suitable from a nutritional standpoint. Six samples of Duroc pork were analysed, each assessed before and after heat treatment. Chemical analysis focused on dry matter, fat, protein, and mineral content (iron, zinc). Both dry (roasting, grilling) and moist (boiling, sous-vide) cooking methods led to a significant increase in dry matter, fat, and protein content compared to raw meat ($P < 0.05$). Iron and zinc concentrations were also significantly higher after all cooking methods ($P < 0.05$). Thermal processing demonstrably alters the chemical composition of pork. The methods differ of thermal processing in their effects on dry matter, fat, and protein levels, and all were shown to increase mineral concentrations, particularly iron and zinc.

Human nutrition, iron, zinc

Cooking of meat leads to protein denaturation, changes in organoleptic properties, and alterations in vitamins and extractive compounds content (Ježek et al. 2019; Vinnikova et al. 2019). Final meat quality is influenced not only by the temperature and cooking method, but also by the heat transfer and heating rate (Ángel-Rendón et al. 2020). Boiling continues to be the go-to method of meat preparation, aiming to chemically alter its structure for improved flavour and to eliminate vegetative forms of microorganisms (James and James 2014). At high temperatures, heterocyclic aromatic amines and other carcinogenic compounds are formed, with their concentrations depending not only on the method and duration of cooking but also on the type of meat (Shabbir et al. 2014). Pork is the most widely consumed meat in the Czech Republic, with per capita consumption reaching 43.9 kg in 2022 (Czech Statistical Office 2023). It contains high-quality complete proteins, vitamins, and essential minerals (Vicente and Pereira 2024). Among contemporary cooking techniques, sous-vide has gained increasing popularity and is now widely applied in both gastronomy and the food industry. This vacuum cooking method helps preserve juiciness and minimizes overcooking (Baldwin 2012).

The aim of this study was to assess the impact of different thermal processing methods (boiling, roasting, grilling, sous-vide) on the chemical properties of pork.

Materials and Methods

Meat processing and heat treatment

The pork used in this study was sourced from the agricultural cooperative in Bělčice. Samples were taken from six pigs of the same Duroc breed, specifically from the same slaughter cut – the m. longissimus lumborum. The pigs were raised and fattened at the Bělčice cooperative, housed freely on plastic slatted flooring. Slaughter took place on February 19, 2025, at 5.5 months of age. Average live weight was 120 kg, and carcass weight was 93 kg. Post-slaughter processing was also carried out in Bělčice. The meat was aged for 3–4 days. Individual loin cuts weighing approximately 5 kg were weighed and divided into 1 kg portions, vacuum-packed (Henkelman Boxer

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35 P, Henkelman Vacuum Systems, 's-Hertogenbosch, Netherlands) in 90 µm vacuum bags (255 × 350 mm), labelled, and stored for two days in a refrigerated chamber at 4 °C. All samples were uniformly frozen at −18 °C prior to thermal analysis and thawed prior to each cooking. A total of six biological samples (n = 6 animals) were analysed, with raw meat and four thermally processed variants evaluated for each animal. Four cooking methods were applied: boiling, roasting, grilling, and sous-vide. The samples were processed under identical and controlled conditions to ensure that the observed differences could be attributed to the heat treatment methods used. All analyses were performed twice – before and after heat treatment.

Boiling was conducted in water at approximately 90 °C for 100 min, with whole loins cooked in a 6-l vessel (Ø240 mm, height 150 mm, OZTI, İstanbul, Türkiye). Grilling was performed using a contact grill (Tefal OptiGrill+, Rumilly, France); meat was sliced and grilled for about 8 min, reaching surface temperatures above 200 °C. Roasting was carried out in a combi oven (RATIONAL, Landsberg am Lech, Germany), with sliced meat roasted at 180 °C for 40 min. The sous-vide process employed a 20-l water bath system (HENDI, GN 1/1, Robakowo, Poland). Meat slices were vacuum-sealed in structured sous-vide bags (250 × 350 mm, 90 µm) and cooked in a water bath at 56.5 °C for 5.5 h. Core temperature was monitored for each sample using a digital probe thermometer (HDT, 300E, OEM).

Chemical analysis

The analysed samples were tested for dry matter, fat, protein, and mineral content. Results are expressed in units of g/100 g. Prior to analysis, samples were homogenized, and each measurement was performed in triplicate. Dry matter content was determined gravimetrically by drying at 105 °C to constant weight, following AOAC (2005) methodology. Fat content was measured using a gravimetric method after xylene extraction in a Soxhlet apparatus, with a glass frit used to retain dry matter (AOAC 1996). Protein content was determined using the Kjeldahl method with an automated Kjeltec 8200 analyser (FOSS, Hillerød, Denmark). Total nitrogen was subsequently converted to protein content using a factor of 6.25 (AOAC 2002).

Determination of mineral content

For digestion, 0.2 g of each sample was weighed into Teflon digestion vessels. To each vessel, 5 ml of concentrated HNO_3 (purified by sub-boiling distillation), 2 ml of H_2O_2, and 1 ml of Milli-Q water were added. The vessels were sealed and transferred to a microwave digestion system (Ethos One, Milestone, Italy), where digestion was carried out at 210 °C for 20 min. Certified Reference Material 1577c Bovine Liver (animal tissue) was used as a reference.

Zinc and iron contents were determined by flame atomic absorption spectrometry (F-AAS) using a 240FS AA instrument (Agilent Technologies, Santa Clara, CA, USA) under optimized conditions. The wavelength was set to 213.9 nm for zinc and 148.3 nm for iron.

Statistical analysis

All measurements were processed in Microsoft Excel, including graph preparation. Statistical analyses were performed using STATISTICA 14.0 (TIBCO Software Inc., Palo Alto, CA, USA). Results are presented as mean ± SD. Data normality and homogeneity of variance were evaluated using Shapiro-Wilk test and Levene's test, respectively. When both assumptions were fulfilled, one-way analysis of variance (ANOVA) was applied, followed by Tukey's honestly significant difference (HSD) post hoc test to account for multiple comparisons. In cases where normality or homogeneity assumptions were not met, non-parametric analysis was conducted using Kruskal-Wallis test, followed by Dunn's post hoc test for multiple comparisons. All statistical analyses were performed at a significance level of $\alpha = 0.05$. Graphs were generated using OriginPro 2024 (OriginLab, Northampton, MA, USA).

Results

Effect of cooking on major meat components

Significant differences ($P < 0.05$) in dry matter, fat, and protein content were observed between the cooking methods (Fig. 1). Dry matter content was highest in roasted meat (44.2%) and lowest in sous-vide samples (32.3%). All cooked samples showed higher contents of dry matter and protein compared to raw meat.

Fat content varied by cooking method, with the highest level in boiled meat (5.4%) and the lowest in sous-vide (3.8%), likely due to differing behaviour of fat compounds under various thermal conditions. Protein content differed significantly across all methods, with the highest value in roasted meat (38.8%) and the lowest in sous-vide (28.2%). The elevated protein concentration in roasted meat was likely due to intensive water evaporation, whereas the gentler conditions of sous-vide cooking resulted in lower water loss and thus lower protein values. Roasting and grilling led to greater moisture loss, while sous-vide preserved water under vacuum at lower temperatures. Overall, sous-vide samples exhibited the lowest average values of dry matter, fat, and protein compared to other cooking methods.

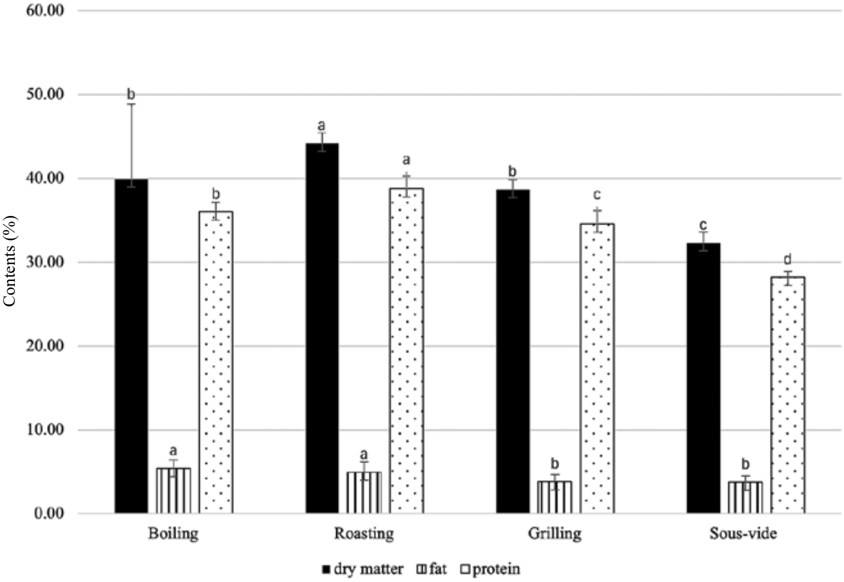

Fig. 1. Dry matter, fat, and protein content (%) in pork subjected to boiling, roasting, grilling, and sous-vide cooking

Different letters above the columns indicate significant differences at $P < 0.05$.

Comparison of dry-heat cooking methods with raw meat

When comparing dry-heat cooking methods such as roasting and grilling with raw pork (27% dry matter), both treatments resulted in a significant increase in dry matter content ($P < 0.05$) (Fig. 2). Roasted meat showed the highest dry matter content (44.2%), while grilled meat had the lowest among cooked samples (38.6%). These differences are attributed to varying degrees of water loss during cooking. Roasting involves high temperatures that promote greater evaporation, leading to higher concentration of meat components. Fat content also increased compared to raw meat (2.4%), with roasted meat reaching 4.9% and grilled meat 3.8%. The fat content in grilled meat may be influenced by water loss during roasting, although grilling typically causes less water evaporation due to shorter exposure times or surface-level moisture loss. Protein content showed the greatest difference between roasted meat (39.8%) and raw meat (23.7%).

Comparison of moist-heat cooking methods with raw meat

Both moist-heat cooking methods – boiling and sous-vide – resulted in a significant increase ($P < 0.05$) in dry matter content compared to raw pork (27.0%) (Fig. 3). Boiled meat showed the highest dry matter content (39.9%), while sous-vide samples had the lowest (32.3%). Fat content was highest in boiled meat (5.4%) and lowest in sous-vide samples (3.8%), compared to raw meat (5.4%). These differences likely reflect variations in heat intensity and moisture loss. Protein content in raw meat was 23.7%, with the lowest post-treatment value observed in sous-vide samples (28.0%).

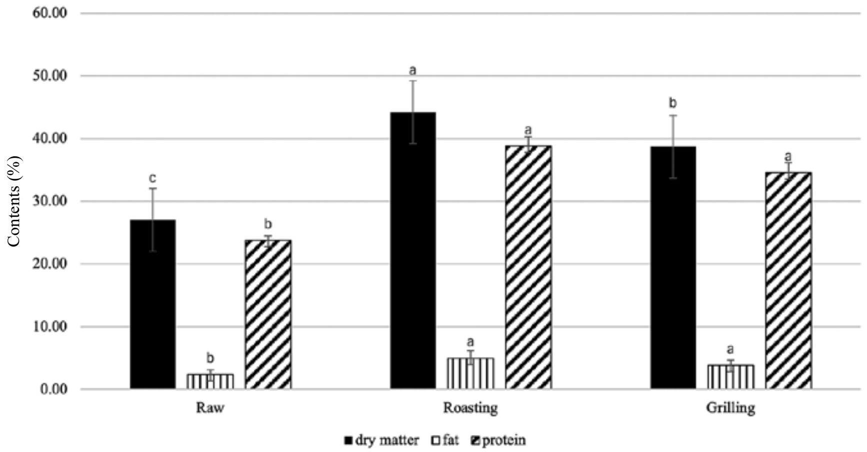

Fig. 2. Dry matter, fat, and protein content (%) in raw pork and after dry-heat treatments (roasting and grilling) Different letters above the columns indicate significant differences at $P < 0.05$.

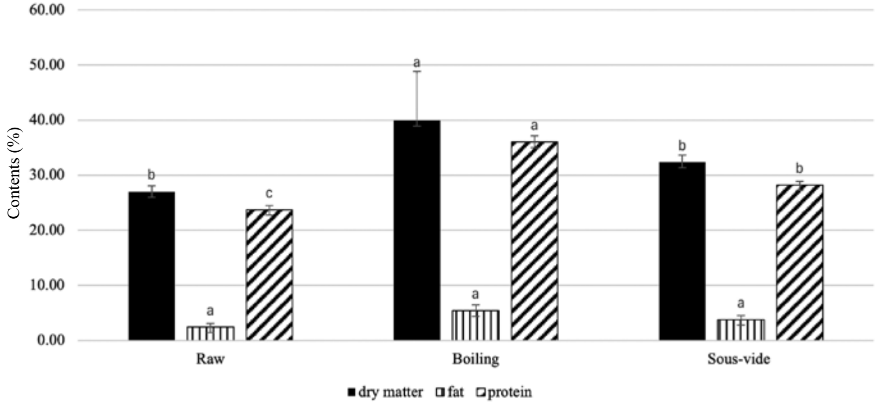

Fig. 3. Dry matter, fat, and protein content (%) in raw pork and after moist-heat treatments (boiling and sous-vide) Different letters above the columns indicate significant differences at $P < 0.05$.

Changes in iron content across different cooking methods

The average iron concentration in raw pork was 3.60 mg/kg (Fig. 4). Following heat treatment, iron levels increased, ranging between 5–7 mg/kg on average. The highest iron concentration was observed in roasted meat (7.21 mg/kg), likely due to water evaporation during roasting, which concentrates nutrients and minerals including iron. Significant differences ($P < 0.05$) were found only between roasted and raw meat samples. Conversely, the lowest iron concentration was recorded in boiled meat (4.89 mg/kg). Minimal, non-significant differences ($P > 0.05$) were found between grilled meat (5.49 mg/kg) and sous-vide samples (5.70 mg/kg). As a result, iron concentrations in these two methods were similar, explaining the lack of significant ($P > 0.05$) differences across other treatments.

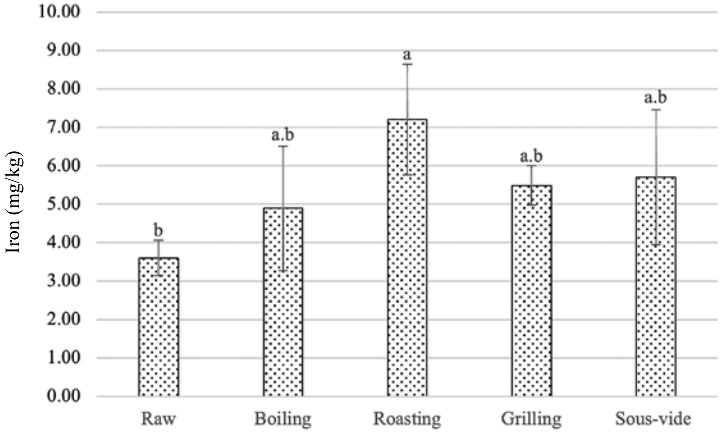

Fig. 4. Iron content (mg/kg) in raw pork and after thermal processing by boiling, roasting, grilling, and sous-vide Different letters above the columns indicate significant differences at $P < 0.05$.

Changes in zinc content across different cooking methods

The average zinc concentration in raw pork was 15.80 mg/kg (Fig. 5). After thermal processing, zinc concentrations increased, ranging between 22–27 mg/kg. The lower zinc content in raw meat is likely due to its higher water content. Cooking reduces water levels, leading to a concentration of minerals, including zinc. The highest zinc concentration was observed in roasted meat (27.00 mg/kg). Significant differences ($P < 0.05$) were found only between roasted and raw meat samples. Conversely, the lowest zinc concentration was recorded in boiled meat (21.52 mg/kg). Minimal, non-significant differences ($P > 0.05$) were observed between grilled meat (22.77 mg/kg) and sous-vide samples (22.15 mg/kg). As a result, zinc concentrations in these two methods were similar, explaining the lack of significant differences ($P > 0.05$) across other treatments. Zinc content followed a similar trend to that observed for iron.

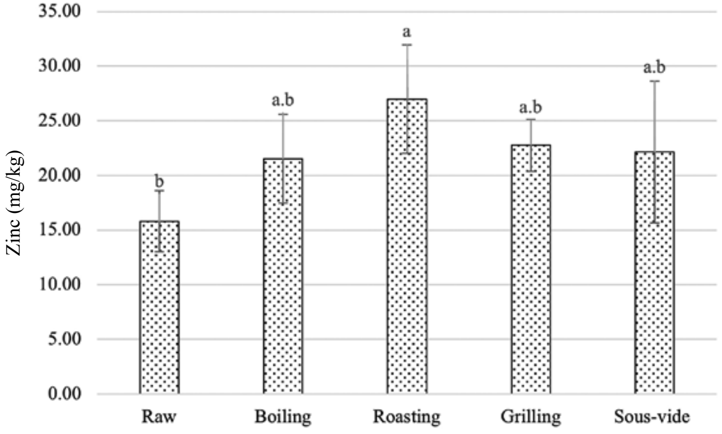

Fig. 5. Zinc content (mg/kg) in raw pork and after thermal processing by boiling, roasting, grilling, and sous-vide Different letters above the columns indicate significant differences at $P < 0.05$.

Discussion

The results of this study are comparable to findings from previous research addressing similar topics. Macharáčková et al. (2021) evaluated dry matter, fat, and protein content in pork processed by sous-vide and grilling. They reported an increase in dry matter for both methods, consistent with our findings. However, their study observed a decrease in fat content, which contrasts with our results, where fat contents increased after heat treatment. These discrepancies may be attributed to differences in the pork cut used or variations in processing conditions. Protein content in Macharáčková et al. (2021) increased with both cooking methods, aligning with our observation of elevated protein contents post-treatment (Macharáčková et al. 2021). Similar conclusions were drawn by Jang et al. (2019), who reported increases in dry matter, fat, and protein following grilling. Van Heerden and Smith (2013) also observed comparable trends in their evaluation of roasted and boiled pork, noting increased dry matter, fat, and protein compared to raw meat. A similar trend was observed in protein and fat content. As in our study, heat treatment (boiling and roasting) resulted in increased protein and fat content. Dry-heat methods, especially roasting, produced the highest dry matter and protein contents due to intensive moisture evaporation under high temperatures, while grilling caused moderate moisture loss because of shorter exposure and surface-limited heating. In contrast, sous-vide cooking resulted in the lowest dry matter, fat, and protein contents, as vacuum sealing and controlled low temperatures minimized water loss, structural shrinkage, and nutrient concentration effects. Although boiling is a moist-heat method, it yielded relatively high dry matter and fat content. Prolonged heating in water promotes protein denaturation and muscle fibre contraction, expelling intracellular water and thereby concentrating solids, including fat. Overall, variations in fat and protein contents across cooking methods primarily reflect differences in water loss rather than true changes in nutrient composition.

Thermal processing of pork also led to elevated concentrations of minerals, specifically iron and zinc. Comparable results were reported by Gerber et al. (2009), Van Heerden and Smith (2013), Tomović et al. (2014), and Jang et al. (2019), who found elevated contents of these elements after boiling, roasting, grilling, or sous-vide cooking. Thermal processing increases the concentration of minerals due to water loss. Dry-heat methods, characterized by intensive dehydration, therefore produced the most pronounced increases in mineral concentrations. Boiling led to a smaller increase in iron and zinc content after processing compared to other methods of preparation. This finding suggests that during boiling, in addition to the transfer of water from the meat, there was also a partial transfer of minerals into the boiling water. The sous-vide method does not increase the concentration as much as roasting or grilling, as it uses lower temperatures and vacuum packaging to preserve nutrients. In contrast, Macharáčková et al. (2021) found that zinc contents remained unchanged after grilling, while iron content decreased. This discrepancy may be due to differences in grilling conditions, such as prolonged exposure to high temperatures or surface charring, which can degrade heme iron and reduce its measurable concentration.

This study was conducted using a limited number of biological samples ($n = 6$), all originating from the same breed, muscle, and production conditions. While this design reduces biological variability, it also limits the statistical power of the study. The relatively small sample size should therefore be considered when interpreting subtle differences among cooking methods. Another important methodological aspect is the use of freezing at −18 °C prior to thermal processing. Freezing and thawing can affect water-holding capacity and promote drip loss, potentially influencing the measured composition. Nevertheless, all samples were subjected to identical storage and handling conditions, ensuring that comparisons among thermal processing methods remain valid. Future research should separately assess the effects of freezing and thawing to better isolate their impact on meat composition.

In conclusion, thermal processing significantly alters the chemical composition of pork meat, mainly through changes in water content and the resulting concentration of nutrients. All evaluated cooking methods increased dry matter, fat, and protein contents compared to raw meat, with the magnitude of these changes strongly dependent on the processing technique. Dry-heat methods, especially roasting, produced the highest concentrations of proteins and minerals due to intensive moisture loss. Sous-vide cooking preserved higher water content and resulted in lower concentrations of macronutrients while maintaining moderate increases in iron and zinc. Boiling led to relatively high macronutrient concentrations in the meat, but lower mineral contents suggest partial redistribution of iron and zinc into the cooking water. These results demonstrate that no single cooking method is universally optimal from a nutritional perspective. Dry-heat treatments increase nutrient density, whereas sous-vide cooking offers advantages in moisture retention and balanced nutrient preservation. In the case of boiling, consumption of the cooking broth may help retain the full mineral content of the meal.

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