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Original research

EFFECT OF DRYING METHODS ON THE VOLATILE COMPOUNDS OF TURKISH PASTIRMA

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Abstract: In standard pastirma production, the drying phase is the longest and most uncontrollable step. This study investigated infrared (IR) and climate-controlled chamber (CC) drying as alternatives to open-air (OA) drying to reduce processing time and evaluate effects on volatile profiles. Pastirma from two muscle types (loin and round) was analysed by HS-SPME-GC/MS, yielding 183 compounds across ten chemical classes. OA and IR drying produced significantly higher aldehyde fractions than CC drying ($p < 0.001$), with hexanal as the predominant lipid oxidation marker. Limonene from cemen paste was detected in all samples. PCA identified drying method as the primary driver of volatile variation; muscle type had no significant effect ($p > 0.05$). IR drying achieved comparable volatile profiles to OA drying in less time, while CC drying minimized oxidation-derived off-flavours, enabling product standardization.

Keywords: *dry-cured meat, infrared drying, climate-controlled drying, aroma, lipid oxidation, SPME-GC/MS*

INTRODUCTION

Pastirma is a well-known Turkish dried meat product in which the raw meat undergoes profound biochemical changes during a multi-stage production process (Kılıç, 2009; Akköse et al., 2018). According to data based on the Turkish Statistical Institute (TÜİK), pastirma production in Türkiye reached 4,055 tons in 2022 (TGDF, 2023). The process involves salting, pressing, drying, and cemen paste coating, which is a mixture of fenugreek (*Trigonella foenum-graecum*), garlic, and red pepper. Classified as a medium-moisture food product, its microbial stability is achieved through reduced water activity, salt penetration and the presence of antimicrobial compounds in the cemen paste (Yetim et al., 2006; Suncak and Gider, 2024; Güngör, 2025). In terms of quality parameters, Turkish food legislation stipulates that pastirma must meet specific compositional criteria: the moisture content must not exceed 50% (excluding the cemen coating), the pH value must not exceed 6.0 and the salt content in the dry matter must not exceed 10% (also excluding the cemen paste coating). Furthermore, the cemen paste coating itself must not constitute more than 10% of the product's weight (Turkish Food

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Codex, 2019). However, the standardisation of processing parameters is inadequate, resulting in significant variation in the quality of commercial products, particularly due to differences in the initial drying stage and the extent of chemical transformations, such as lipid oxidation and protein degradation (Kaya & Kaban, 2016; Hazar et al., 2017).

The characteristic aroma of pastirma originates from three interconnected biochemical processes: lipid oxidation, protein degradation and the absorption of volatile compounds from the cemen paste (Demirok et al., 2013). Lipid oxidation, primarily the autoxidation of unsaturated fatty acids in intramuscular and subcutaneous fat, generates volatile aldehydes, ketones and alcohols that form the basis of the aroma profile (Shahidi & Pegg, 1994).

Prior to oxidation, the action of endogenous and microbial lipases and phospholipases hydrolyses the triglycerides and phospholipids found in muscle and adipose tissue. This process releases free fatty acids (FFAs), which serve as key substrates for sub-sequent oxidative reactions (Toldrá & Flores, 1998; Gandemer, 2002).

Compared to esterified lipids, these FFAs are particularly susceptible to oxidation, and their breakdown yields the volatile aldehydes, alcohols, and ketones that are widely recognised as major contributors to the characteristic rancid, aged ham, and dry-cured odours typical of cured meat products (Gandemer, 2002; Fu et al., 2022).

In pastırma specifically, the activity of neutral lipase, acid lipase and phospholipase varies with processing conditions, thereby shaping the resulting profile of volatile compounds (Kabil et al., 2025). Processing has also been reported to substantially alter the composition of phosphorlipids and fatty acids (Aksu et al., 2017).

Furthermore, in dry-cured meats more broadly, curing and drying conditions have been reported to accelerate lipid oxidation by promoting membrane disruption and free radical generation, favouring the formation of reactive aldehydes that further enrich flavour development (Zhang et al., 2026); a similar mechanism can plausibly be assumed to contribute to the flavour profile of pastırma, given the comparable processing conditions involved. Meanwhile, myofibrillar and sarcoplasmic proteins are broken down into peptides and free amino acids by endogenous proteolytic enzymes (such as cathepsins and calpains) and microbial peptidases. This provides precursors for the Maillard reaction and Strecker degradation (Güngören, 2025; Yalınkılıç et al., 2025). The most distinctive aroma characteristics are acquired through the diffusion and retention of aromatic compounds from the cemen paste, including terpenes from fenugreek and organosulfur compounds from garlic. These compounds undergo chemical modifycations and interact with the meat matrix during the final drying stage (Kaban, 2009).

Previous research has established that aldehydes constitute the dominant chemical class in the volatile fraction of pastirma, with hexanal the primary oxidation product of linoleic acid serving as a key marker compound. Demirok et al. (2013) characterised the volatile profiles of traditional pastirma produced from different muscle types, confirming the dominance of aldehydes and the significant contribution of sulphur-containing compounds derived from garlic. Hazar et al. (2019) demonstrated that adding nitrates increased the quantity of total volatile compounds and specifically altered hexanal levels, highlighting the impact of curing agents and processing temperature. Kabil et al. (2025) examined the impact of salt reduction on four types of pastirma (kuşgömü, sırt, bohça and şekerpare), finding that salt concentration significantly affected the volatile profile.

Collectively, these findings emphasise that processing parameters are more decisive than raw material selection in determining the characteristics of the final product. However, the effect of various drying techniques on pastirma aroma compounds remains under-researched.

This study examined the production of pastirma from loin and round muscles using three distinct primary drying technologies: open-air drying (OA), climate-controlled chamber drying (CC) and infrared drying (IR). The same cemen paste application and secondary drying protocols were used for all samples to isolate the effect of the primary drying method. The volatile compound profiles were characterised using headspace solid-phase microextraction coupled with gas chromatography-mass spectrometry (HS-SPME-GC/MS). The aim of this study is to elucidate the contribution of drying technology to pastirma aroma development, and to provide evidence that could inform improvements to the processing of traditional meat products.

MATERIALS AND METHODS

Pastirma production

Pastirma production was carried out as described in the study by Batman et al. (2025). The study used the loin (*longissimus thoracis et lumborum*) and round (the *vastus* muscle group) muscles of two-year-old Charolais heifers. The meat was matured at 0 - 2 °C for 24 hours after slaughter. The meat was trimmed at 12 °C to create deep incisions and then treated with curing salts at ambient temperature. It was left to stand at 12 °C for 24 hours. After curing, the meat was rinsed and hung at ambient temperature.

During the pre-drying stage, the meat blocks were left to rest for two days in conditions of 20 ± 2 °C, 75% relative humidity, and an airflow velocity of 1.5 ± 0.5 m/s-1. Excess water was then removed by pressing the blocks at 20 °C for 24 hours under a pressure of 1.0 kg/cm². Primary drying, the longest stage in the production of pastirma, was carried out using three different methods: (i) open-air drying (OA): seven days at a temperature of 37 ± 3 °C, 55 ± 5% relative humidity, and an airflow velocity of 1.5 ± 0.5 m/s^{-1}; (ii) climate-controlled chamber drying (CC): 38 ± 3 °C, 75% relative humidity, and an airflow velocity of 1.5 ± 0.2 m/s^{-1} for five days; and (iii) infrared drying (IR): a temperature of 38 ± 3°C, a relative humidity of 70 - 75% and an airflow velocity of 1.5±0.2 m/s^{-1} for two days. Although the drying time and relative humidity conditions differed considerably among the three primary drying methods, the drying endpoint for each method was not defined by a fixed moisture or water activity target but rather by sensory equivalence: the CC and IR drying processes were concluded once the samples visually and texturally matched the sensory properties of the traditionally OA dried pastırma, as judged by experienced pastırma masters (Batman et al., 2025). Despite reaching this comparable sensory endpoint, the resulting moisture content and water activity still differed significantly among the three methods: OA dried samples showed significantly lower final moisture content (35.69 - 37.57%) and water activity (a_w; 0.842 - 0.846) compared with CC (42.61 %; a_w 0.852 - 0.871) and IR dried samples (39.0 - 41.17%; a_w 0.867), the latter two of which did not differ significantly from one another. This discrepancy was attributed to the shorter drying duration and higher relative humidity applied in the CC and IR treatments relative to the seven days OA process. Moisture distribution was also more homogeneous across the cross-section of CC and IR dried blocks, whereas OA dried samples retained a distinctly moister central core relative to the drier outer surface, consistent with case hardening under prolonged open-air exposure (Batman et al., 2025). These findings confirm that, prior to cemen application; all samples had reached a sensorially comparable, though not physicochemically identical, drying endpoint. Subsequent to the completion of the initial drying process, the meat blocks were coated with a mixture of fenugreek seed powder, garlic, and paprika powder, known as cemen paste. The coated meat blocks were then stored at a temperature of 2 °C for a duration of one day.

All samples were subjected to the final drying stage under identical conditions: a temperature of 20 ± 2 °C, relative humidity of 60 ± 5%, and an airflow velocity of 1.5 ± 0.5 m/s^{-1} for period of 24 hours within a climate-controlled chamber.

Determination of volatile aroma compounds (SPME-GC/MS)

The total volatile aroma compounds in the pastirma samples were analysed using headspace solid-phase microextraction gas chromatography/mass spectrometry (HS-SPME-GC/MS). This analysis was performed according to the protocol described by Machiels and Istasse (2003). Five grams of pastirma were placed in headspace vials, which were first held at 50 °C for 60 minutes and then immersed in a fibre vial and held at the same temperature for a further 60 minutes. At the end of this period, the sample was transferred to the fibre GC injector for desorption. The oven temperature programme began with isothermal holding at 35 °C for three minutes, followed by heating to 50 °C at a rate of 10 °C/min, then to 200 °C at a rate of 4 °C/min and finally to 250 °C at a rate of 50 °C/min. It was then held at 250 °C for ten minutes. A HP5MS capillary column (30 m × 0.25 mm × 0.25 µm) was used, with helium selected as the carrier gas at a flow rate of 1.5 mL/min. The peaks observed in the chromatogram were identified by searching the Flavor 2, HPCH 1607 and Wiley7NIST libraries, and were expressed as relative area percentages (%).

Statistical Analysis

The experimental design comprised two muscle types (loin and round) processed under three

drying methods (OA, CC and IR), yielding six experimental groups (OA-L, OA-R, CC-L, CC-R, IR-L, IR-R). Volatile compound analyses were performed in duplicate for each sample, and results are expressed as mean ± standard deviation (mean ± SD). A one-way analysis of variance (ANOVA) was performed to determine the effect of the drying method and muscle type on the profile of volatile compounds. Differences between groups were assessed using the Tukey–Kramer honestly significant difference (HSD) test at a significance level of $p < 0.05$. An independent samples t-test was used to compare the loin and round muscles. Principal component analysis (PCA) was applied to the normalized volatile compound data to visualize the clustering patterns among the six sample groups and to identify which volatile compounds contribute most strongly to sample differentiation. For heatmap visualization, volatile compound data were scaled by row-wise Z-scores to enable comparison of the relative abundance patterns of each compound across sample groups. All statistical analyses were performed using GraphPad Prism software (GraphPad Software, San Diego, CA, USA).

RESULTS AND DISCUSSION

Identification of volatile compounds in pastirma samples

HS-SPME-GC/MS analysis using an HP5MS column and spectral libraries identified 183 volatile compounds across all six pastirma samples (Table S1). These compounds were classified into ten chemical groups: aldehydes, ketones, alcohols, terpenes and terpenoids, acids and esters, sulphur compounds, heterocyclic compounds, and hydrocarbons, aromatic hydrocarbons and others. The number of identified compounds varied substantially among samples. The IR-R sample exhibited the highest compound diversity (93), followed by CC-L (52), OA-R (51), IR-L (46), and OA-L (46) while CC-R (11) showed the lowest diversity. Table 1 shows the 33 key volatile compounds with the highest relative area percentages, comprising 10 aldehydes, 5 ketones, 5 alcohols, 6 terpenes/terpenoids, 3 sulfur compounds, 1 heterocyclic compound, and 3 aromatic hydrocarbons.

Chemical class distribution analysis revealed significant differences in volatile profiles across drying methods (Fig. 1A). Aldehydes dominated the OA samples, constituting 28.3% of OA-L and 37.2% of OA-R. This was followed by the IR samples (IR-L: 16.1%; IR-R: 10.0%) and the climate-controlled chamber samples (CC-L: 14.0%; CC-R: 14.2%), which had markedly lower proportions. Terpenes and terpenoids were the second most abundant class in OA samples (26.0% in OA-L and 17.6% in OA-R). Notably, their proportion exceeded that of aldehydes in IR samples (IR-L: 31.2%; IR-R: 30.1%). A similar trend was evident in the CC group, with terpenes and terpenoids ranking second in CC-L (13.8%) and becoming dominant in CC-R (41.7%). Conversely, hydrocarbons were the most abundant class in IR-L (35.0%).

Comparative radar chart analysis (Fig. 1B) further corroborated these patterns, revealing that alkanes were most abundant in IR-L (35.0%) and OA-L (27.8%), reflecting a pronounced presence of saturated hydrocarbons in these groups, whereas aromatic compounds were disproportionately elevated in CC-R (24.4%). Notably, CC-L exhibited the highest ketone content (17.5%) among all samples, along with a distinct peak in pyrazines (2.8%), further distinguishing the CC group from OA and IR samples. Collectively, these findings indicate that each drying method produces a unique chemical fingerprint, with aldehydes and terpenes serving as the primary discriminating volatile classes.

A heat map analysis was conducted to evaluate the relative abundance of the volatile compounds detected. This revealed distinct chemical profiles among the pastirma drying methods (OA, IR and CC) (Fig. 1C). The analysis showed that aldehyde compounds (hexanal, nonanal and octanal) had higher Z-scores, particularly in the OA group. This suggests that aldehydes could be potential markers for the open-air drying method.

Conversely, an in-crease in the concentration of cyclohexene and 1-methyl-4-(1-methylethenyl) (S)- and benzene and 1-methyl-3-(1-methylethyl) compounds was detected in the samples from the right-hand side (CC-R) of the CC group. These high concentrations in the CC-R region sharply differentiate the climatic control chamber drying method from the others. IR samples, however, exhibited a more heterogeneous distribution. Specifically, the heptane compound 2,2,4,6,6-pentamethyl reached the highest levels in the IR-L group, while the benzene compound 1-methyl-4-(1-methylethyl) was present at moderate-to-high levels in both IR groups.

Table 1.
The main volatile compounds identified in the pastirma samples

Compound	Pastirma samples					
	OA-L	**OA-R**	**IR-L**	**IR-R**	**CC-L**	**CC-R**
Aldehydes						
Hexanal	9.60±0.50	13.76±0.47	5.61±0.21	1.67±0.06	ND	ND
Nonanal	8.98±0.59	10.00±0.51	3.64±0.09	3.02±0.09	1.51±0.17	1.59±0.03
Octanal	3.61±0.26	3.18±0.08	2.11±0.29	0.91±0.02	0.42±0.01	1.15±0.06
Heptanal	2.01±0.03	2.36±0.01	0.87±0.09	ND	ND	ND
Benzaldehyde	ND	ND	1.42±0.05	0.94±0.01	ND	ND
Benzeneacetaldehyde	1.08±0.03	0.98±0.04	0.72±0.02	0.22±0.01	ND	ND
Decanal	0.18±0.01	0.30±0.04	0.10±0.00	0.17±0.00	0.12±0.00	ND
(E)-2-Nonenal	0.36±0.04	ND	ND	ND	ND	ND
(E)-2-Decenal	0.11±0.00	ND	ND	ND	ND	ND
Benzaldehyde, 4-(1-methylethyl)-	ND	ND	ND	0.08±0.01	ND	ND
Ketones						
2-Nonanon	1.56±0.15	1.11±0.04	1.55±0.09	1.32±0.05	0.43±0.03	0.92±0.02
2-Heptanon	0.25±0.02	0.45±0.05	1.28±0.12	ND	ND	ND
2,2-Dimethyl-3-	ND	7.21±0.13	ND	ND	ND	ND
4-Nonanon	0.20±0.01	ND	ND	ND	ND	ND
4-Octanone, 5-hydroxy-2,7-dimethyl-	ND	ND	0.05±0.00	0.63±0.04	ND	ND
Alcohols						
1-Okten-3-ol	1.93±0.03	2.35±0.36	0.81±0.08	0.09±0.00	ND	ND
1-Hexanol	0.66±0.10	ND	ND	ND	ND	ND
(Z)-2-Okten-1-ol	0.37±0.08	ND	ND	ND	ND	ND
2-Ethyl-1-hexanol	ND	ND	ND	1.39±0.10	0.43±0.00	ND
(Z)-2-Cyclohexene-1-ol	ND	0.09±0.00	0.22±0.02	ND	ND	ND
Terpenes and terpenoids						
Compound	**Pastirma samples**					
	OA-L	**OA-R**	**IR-L**	**IR-R**	**CC-L**	**CC-R**
d/l-Limonene	19.15±1.19	9.87±0.22	19.90±0.46	14.55±0.96	4.36±0.15	ND
γ-Terpinen	ND	ND	ND	ND	ND	10.76±1.28
β-Pinene	0.97±0.08	ND	0.94±0.05	1.75±0.16	ND	ND
α-Pinene	1.36±0.16	ND	0.68±0.00	ND	ND	ND
p-Cymene	ND	3.65±0.13	3.51±0.07	2.58±0.05	0.10±0.00	ND
Δ3-Carene	ND	0.65±0.08	ND	ND	ND	ND
Sulfur Compounds						
1-Octanethiol	1.31±0.08	1.44±0.09	ND	ND	ND	ND
Diallyl disulfide	ND	ND	0.99±0.06	0.80±0.05	ND	0.86±0.06
2-Ethyl-1H-isoindole-1,3(2H)-dithione	1.80±0.12	ND	1.71±0.11	ND	ND	ND
Heterocyclic compounds						
2,3,5,6-tetramethyl pyrazine	0.20±0.01	ND	0.11±0.01	ND	0.05±0.00	ND
Aromatic hydrocarbons						
Benzene, 1,3-bis(1,1-dimethylethyl)-	3.33±0.21	5.52±0.35	5.30±0.34	2.72±0.17	ND	0.51±0.03
Benzene, 1-methyl-3-(1-methylethyl)-	3.54±0.23	ND	ND	ND	1.36±0.09	5.79±0.37
Benzene, ethenyl-	0.63±0.04	0.07±0.00	0.47±0.03	1.09±0.07	ND	ND

ND: not determined



Figure 1. A: Relative content of volatile components in pastirma samples, expressed as relative area (%) of the total identified volatile fraction in each sample. The areas of slices representing >2% are indicated. B: Comparative analysis of volatile compound profiles across different pastirma samples. The radar plot illustrates the relative distribution (%) of major chemical classes for OA, IR, and CC samples. Each polygon represents the mean relative area (%), and shaded regions denote the standard deviation (SD) C: Comparative heat map analysis of volatile compound profiles pastirma samples. The colour scale represents Z-scores indicating the relative abundance of each compound (Red: high density; Blue: low density). Muscle types: loin (L) and round (R). Drying methods: open-air drying (OA), climate-controlled chamber drying (CC), and infrared drying (IR)

These findings demonstrate that drying method represents the primary determinant of volatile compound diversity. Open-air and infrared drying methods generated significantly richer and more diverse volatile profiles compared to climate-controlled chamber drying, indicating that drying duration directly influence the biochemical reactions governing aroma compound formation in pastirma. This observation aligns with previous reports emphasizing the decisive role of processing parameters and conditions in volatile compound development in pastirma and dry-cured products (Kaban, 2013; Hazar et al., 2019).

Aldehydes

Aldehydes constituted the predominant chemical class in both the open-air and infrared drying methods. Their respective shares of the total identified volatile fraction were recorded as 37.2% in OA-R, 28.3% in OA-L, 16.1% in IR-L, 10.0% in IR-R, 14.0% in CC-L and 14.2% in CC-R (see Fig. 1A). The highest concentrations of hexanal, an indicator of linoleic acid oxidation, were found in the OA-R (13.76%) and OA-L (9.60%) samples. OA-R showed a statistically significant elevation compared to OA-L ($p < 0.001$). The OA-L sample also differed significantly from the IR-R sample ($p < 0.01$), as did the OA-R sample from the climate-controlled chamber samples ($p < 0.001$). However, hexanal levels declined sharply in the IR group, with no statistically significant difference observed between IR-L and IR-R ($p > 0.05$). Hexanal was also undetectable in the climate-controlled chamber samples. Nonanal and octanal were also found to be significantly more abundant in open-air

dried pastırma samples than in other samples (Fig. 2). Significant differences in nonanal levels were observed between OA-L and OA-R ($p < 0.01$), OA-R and CC-L ($p < 0.01$) and OA-L and CC-R ($p < 0.01$), confirming that open-air dried samples contained significantly higher levels of nonanal than chamber-dried samples. Similarly, significant differences were detected for octanal between OA-L and OA-R ($p < 0.01$), OA-L and IR-L ($p < 0.001$) and OA-L and CC-R ($p < 0.001$). No significant difference was observed between IR-L and IR-R. Heptanal was only detected in the OA-R (2.36%), OA-L (2.01%) and IR-L (0.87%) samples (Fig. 2). OA-R contained significantly higher levels than OA-L ($p < 0.01$), and the decline from OA-L to IR-L was highly significant ($p < 0.001$). However, it was undetectable in the IR-R and climate-controlled chamber samples (Fig. 2). Decanal, which is the main product of oleic acid oxidation and can also be derived from the oxidation of both oleic and linoleic acids (Wu et al., 2014), was detected in all samples except CC-R (Fig. 2). OA-R contained significantly more decanal than OA-L ($p < 0.05$). OA-L also differed significantly from IR-R ($p < 0.01$) and CC-L ($p < 0.05$). Benzeneacetaldehyde, which has been reported to impart sour, stale and pungent flavour characteristics to meat products (Li et al., 2020), was identified as another significant contributor to the overall aroma profile of both open-air and infrared-dried samples (Fig. 2). Levels peaked in the OA groups, with a slight but significant difference between OA-L and OA-R ($p < 0.05$). OA-L levels were also significantly higher than in IR-L and IR-R (both $p < 0.001$), and benzeneacetaldehyde was undetectable in CC samples.

The predominance of aldehydes across samples is consistent with their well-established role as key aroma-active compounds in meat, where they are primarily generated through the oxidative breakdown of unsaturated fatty acids and the thermal degradation of sugars (Shiqi et al., 2024). Also, findings of this study were consistent with previous studies identifying aldehydes as the dominant chemical group in pastirma (Kaban, 2009; Demirok et al., 2013; Hazar et al., 2019). The presence of hexanal, a secondary breakdown product formed during the degradation of unsaturated lipids such as linoleic acid (Shahidi & Hossain, 2022), is widely accepted as an indicator of lipid oxidation and rancidity.

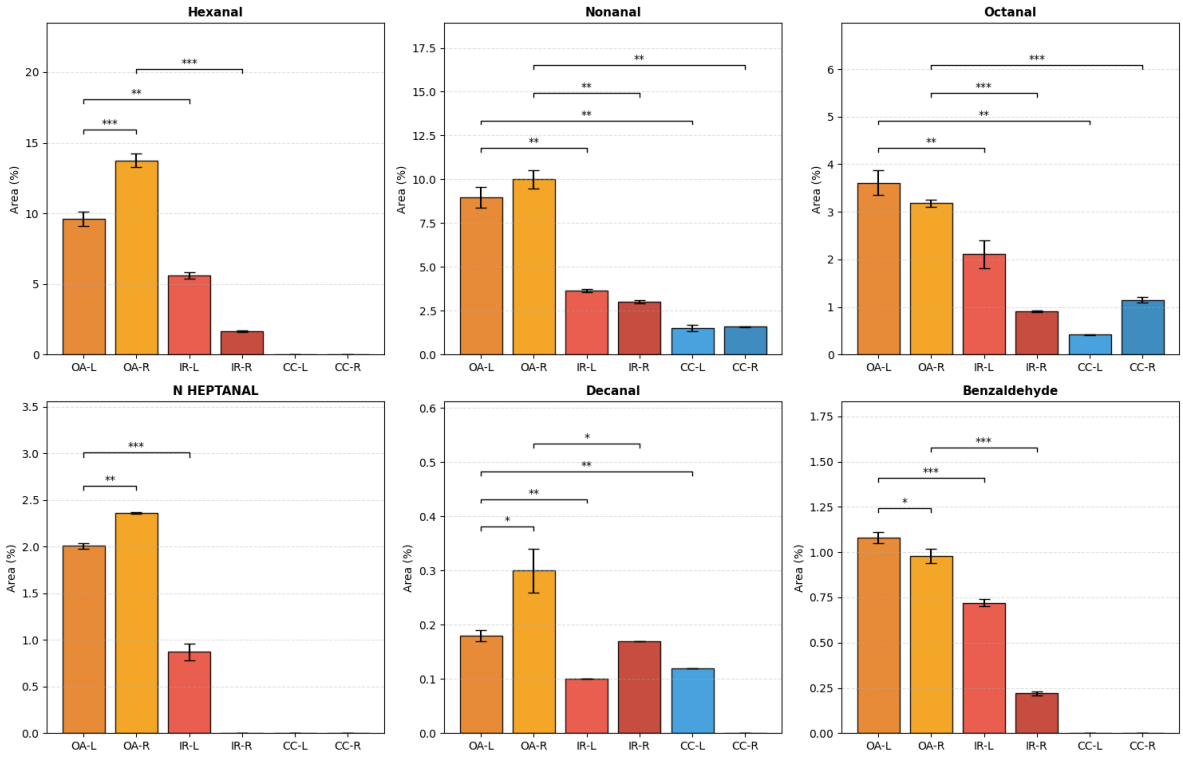


Figure 2. Relative area (%) amounts of main aldehyde compounds identified in pastirma samples. Data are presented as Mean ± Standard Deviation. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Muscle types: loin (L) and round (R). Drying methods: open-air drying (OA), climate-controlled chamber drying (CC), and infrared drying (IR)

In dry-cured products, it has been reported that linear aliphatic aldehydes are typical products of lipid oxidation derived from the oxidation of unsaturated fatty acids, and that their content increases in parallel with the drying process (Sha et al., 2017). Furthermore, it has been reported that peroxides, which trigger lipid oxidation, react with peptides and amino acids to form various volatile aldehyde compounds, primarily hexanal, octanal, and nonanal (Zhu et al., 2024). In this context, the high aldehyde concentrations in the samples dried in open-air or using infrared radiation can be attributed to lipid oxidation. This is due to the different drying conditions associated with these methods compared to those in a climate-controlled chamber, particularly the penetrating effect of infrared radiation and the prolonged open-air drying time of seven days. Despite similar temperature conditions, it is thought that the lipid oxidation was increased by the longer duration of open-air drying and the uncontrolled external environmental conditions. When these findings are considered together, it is clear that the drying method significantly influences lipid oxidation, regardless of temperature, duration, type of radiation, or environmental conditions. The significant impact of processing conditions on lipid oxidation has previously been reported in dried curing products (Sun et al., 2001; Pereira and Abreu, 2018; Zioud et al., 2023).

Terpenes and terpenoids

Terpenes and terpenoids were the second-largest chemical class by percentage in both the open-air and infrared-dried samples. D/L-limonene was identified as the dominant compound in all the samples in which it was present, ranging from 4.36% in CC-L to 19.9% in IR-L (Fig. 3). The highest concentrations of limonene were recorded in IR-L (19.9%) and OA-L (19.1%), while OA-R was significantly lower than OA-L ($p < 0.01$), and IR-L was significantly higher than IR-R ($p < 0.01$). OA-L also differed significantly from IR-R ($p < 0.01$) and CC-L recorded the lowest limonene concentration of all the samples ($p < 0.05$ vs. OA-L). γ-Terpinene followed a similar distribution pattern, peaking in IR-L and OA-L at 2.14% and 1.94% respectively. There were highly significant differences between OA-L and OA-R, OA-L and IR-L, IR-L and IR-R, OA-L and IR-R, and OA-L and CC-L. In contrast, p-cymene was undetectable in OA-L, whereas the highest levels were found in OA-R (3.65%) and IR-L (3.51%). There was a significant difference between OA-R and IR-R ($p < 0.01$), as well as between IR-L and IR-R ($p < 0.001$). Only trace amounts were detected in CC-L (0.1%). β-pinene exhibited a distinct distribution pattern, reaching its highest con-centration in IR-R (1.75%). This was significantly different from the IR-L samples (0.94%) ($p < 0.01$). β-Pinene was undetectable in OA-R and CC samples.

Terpenes and terpenoids identified in pastırma samples are attributable to the cemen paste, which consists of fenugreek seed powder (*Trigonella foenum-graecum*), garlic, red pepper, and water. The detected terpene compounds, including limonene, α-pinene, β-pinene, p-cymene, α-terpinene, terpinolene, and thujene, are consistent with the known volatile profiles of the pepper (Marušić et al., 2011; Domínguez et al., 2019). Limonene in particular serves as the primary indicator of cemen paste-derived terpenes in pastirma aroma. Indeed, Hazar et al. (2019) examined the terpene profile of pastirma subjected to different curing processes and reported that compounds such as limonene, α-phellandrene and 3-carene originate from cemen paste components. Other studies have confirmed that terpene hydrocarbons primarily originate from the spices used in the cemen paste, such as fenugreek seed powder, red pepper and garlic (Hazar et al., 2019; Kaban, 2009).

Although the drying stage with cemen paste was carried out under the same conditions for all samples (in climate-controlled chamber), the observation of significant differences in terpene concentrations is a notable finding. This suggests that the physicochemical changes induced in the pastirma texture by the different techniques applied during the primary drying stage primarily moisture content, water activity, and surface structure may have influenced the diffusion of curing agents into the product, as well as the release and retention behaviour of volatile terpene compounds. Notably, limonene reached its highest values in the OA-L and IR-L samples, suggesting that microstructural changes and decreased water activity caused by drying may have facilitated the penetration of spice components into the meat in the subsequent stage. Flores (2018) and Flores et al. (2021) supported this observation, emphasising that the formation of volatile compounds in cured meat products is related not only to the addition of spices, but also to factors such as

moisture content, water activity, and lipid oxidation. Similarly, the relatively low concentrations of terpenes observed in climate-chamber drying suggest that the slow, controlled drying process may create a tighter product texture, limiting the ability of volatile compounds to penetrate during curing. Marušić et al. (2011) reported that the terpenes in Istrian dry-cured ham originate from spices, but that the moisture content of the product and the drying conditions influence the concentration of these components.

Ketones and alcohols

Five ketone compounds were identified in pastırma samples, two of which emerged as dominant (Fig. 1A). Figure 4 shows that statistically significant differences were observed in the levels of 2-nonanone and 2-heptanone across groups and lateralisation. The primary methyl ketone present in all six samples was 2-nonanone. The lowest concentration was found in CC-L (0.43%), while the highest was found in OA-L (1.56%). Within the OA group, OA-L exhibited significantly higher levels of 2-nonanone than OA-R ($p < 0.05$). OA-L also exhibited significantly higher levels than CC-L ($p < 0.01$). In right-side comparisons, IR-R contained significantly more 2-nonanone than OA-R, which in turn contained significantly more than CC-R ($p < 0.01$). 2-Heptanone was present in the OA-L (0.25%), OA-R (0.45%) and IR-L (1.28%) samples but was absent from the climate-controlled chamber (CC) samples (CC-L and CC-R) and the IR-R sample. Unlike 2-nonanone, the OA-R sample showed significantly higher levels of 2-heptanone compared to the OA-L sample ($p < 0.05$).

The most pronounced difference was observed in the IR-L sample, which exhibited a dramatic and significant increase compared with the OA-L sample ($p < 0.01$). 4-Nonanone was detected exclu-sively in OA-L (0.20%), while 2,2-dimethyl-3-octanone was found only in OA-R. Notably, it reached a comparatively high concentration of 7.21% in this sample, despite being absent from all others.

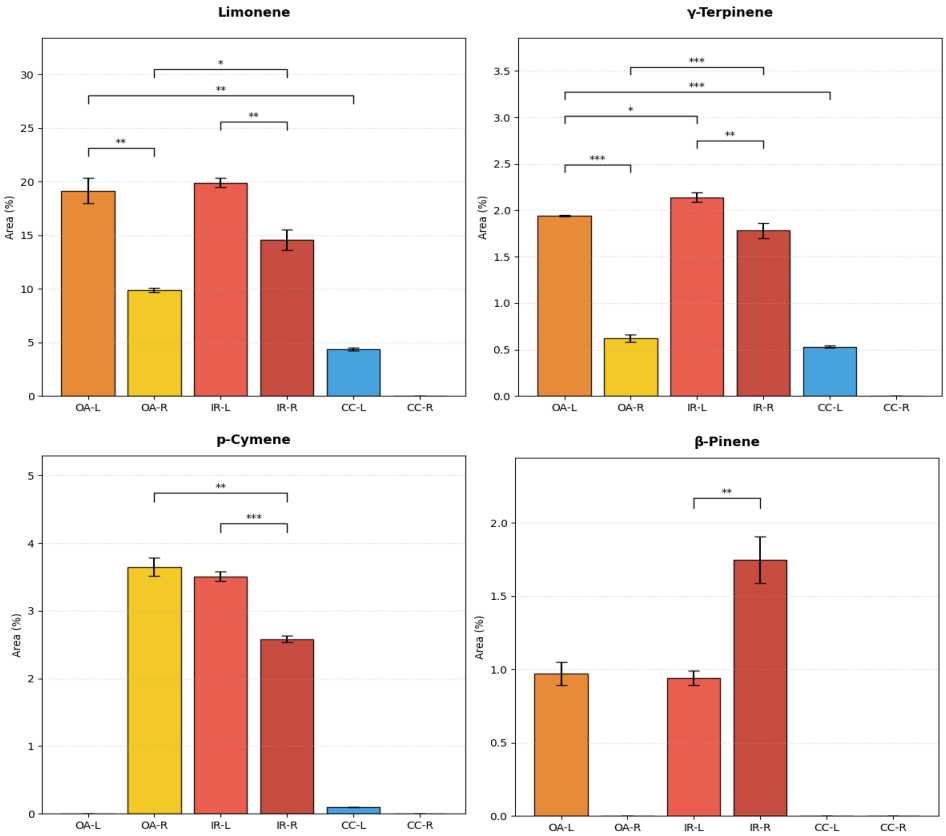


Figure 3. Relative area (%) amounts of main terpenes and terpenoids compounds identified in different pastirma samples. Data are presented as Mean ± Standard Deviation. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Muscle types: loin (L) and round (R). Drying methods: open-air drying (OA), climate-controlled chamber drying (CC), and infrared drying (IR)

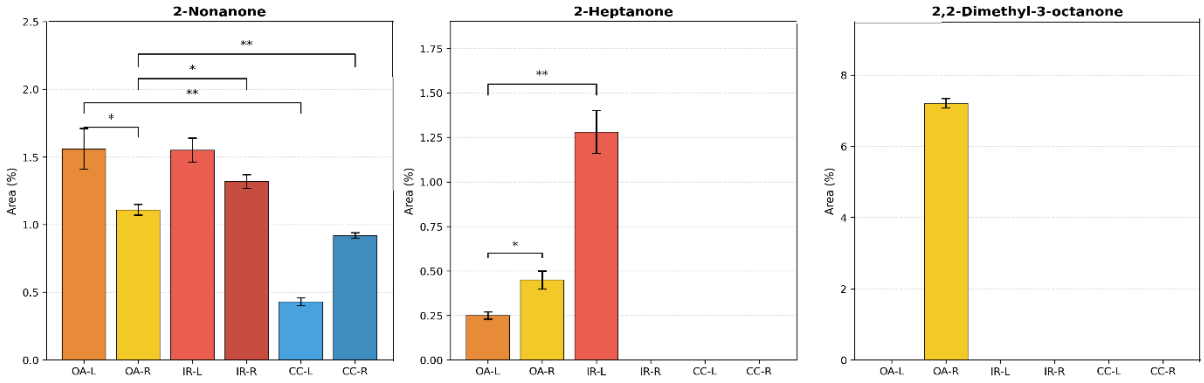


Figure 4. Relative area (%) amounts of main ketone compounds identified in different pastirma samples. Data are presented as Mean ± Standard Deviation. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Muscle types: loin (L) and round (R). Drying methods: open-air drying (OA), climate-controlled chamber drying (CC), and infrared drying (IR)

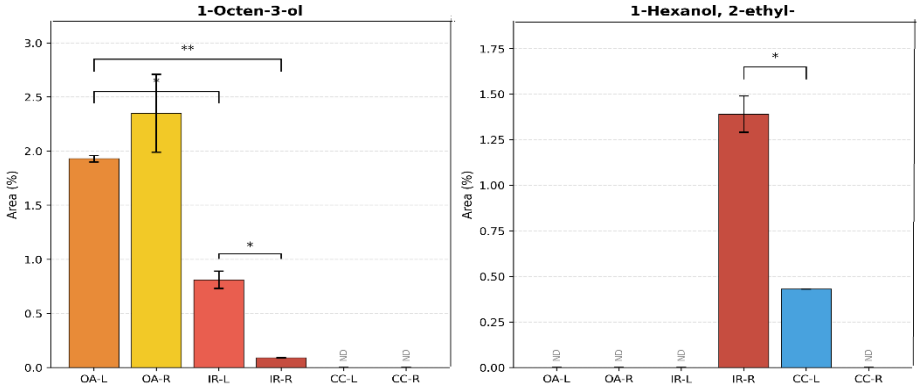


Figure 5. Relative area (%) amounts of main alcohol compounds identified in different pastirma samples. Data are presented as Mean ± Standard Deviation. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Muscle types: loin (L) and round (R). Drying methods: open-air drying (OA), climate-controlled chamber drying (CC), and infrared drying (IR)

The most predominant compound in the alcohol class was 1-octanol (Fig. 5). This compound was present in the OA-L (1.93%), OA-R (2.35%), IR-L (0.81%) and IR-R (0.09%) samples but not in the CC-L and CC-R samples. OA-L had significantly higher levels of 1-octen-3-ol than both IR-L ($p < 0.05$) and IR-R ($p < 0.01$). IR-L also had significantly higher levels than IR-R ($p < 0.05$). In contrast, no significant difference was observed between OA-L and OA-R. Of the other identified alcohol compounds, 2-ethyl-1-hexanol was present in the IR-R (1.39%) and CC-L (0.43%) samples. IR-R exhibited significantly higher levels than CC-L ($p < 0.05$).

In meat products, methyl ketones are primarily formed through the β-oxidation and decarboxylation of unsaturated fatty acids. These compounds contribute to the characteristic fruity and cheesy aromas (Hazar et al., 2019; Sha et al., 2017). The presence of 2-nonanone in all samples, with varying concentrations depending on the drying method, suggests that this compound originates from lipid oxidation and is affected by drying conditions. Similarly, Demirok et al. (2013) identified methyl ketones, such as 2-heptanone and 2-octanone, in traditional pastirma, reporting that these compounds are oxidation products of linoleic acid. The highest concentration of 2-heptanon (1.28 ± 0.12%) was found in the IR-L sample, suggesting that infrared radiation specifically stimulates the β-oxidation/decarboxylation pathway. Conversely, the absence of 2-heptanon in the climate-controlled chamber samples suggests that controlled drying conditions limit the formation of advanced oxidation products.

Sulphur compounds and heterocyclic compounds

Three sulphur compounds were identified in pastirma samples. These were 1-octanethiol, diallyl disulfide and 2-ethyl-1H-isoindole-1,3(2H)-dithione. Diallyl disulphide was present

in the IR-L (0.99%), IR-R (0.80%) and CC-R (0.86%) samples but not in the OA-L, OA-R or CC-L samples. 1-octanethiol was specific to the OA-L (1.31%) and OA-R (1.44%) samples, and was not detected in the other samples. Although 2-ethyl-1H-isoindole-1,3(2H)-dithione is structurally heterocyclic, it is classified in this group due to its sulfur content. It was detected at high concentrations in the OA-L (1.80%) and IR-L (1.71%) samples.

Within the class of heterocyclic compounds 2,3,5,6-tetramethyl pyrazine, which is derived from the Maillard reaction, was detected at similar levels in the OA-L and IR-L samples (0.20% and 0.11%, respectively), and at trace levels in the CC-L sample (0.05%).

One of the most important factors in shaping the characteristic aroma of pastirma is the cemen paste. The cemen paste imparts a distinctive quality to the aroma of pastirma through organosulphur compounds derived from garlic (Kaban, 2009; Demirok et al., 2013). While all samples underwent the same secondary drying process after the cemen paste was applied, it is interesting to note that sulphur compounds, particularly diallyl disulphide, showed significant variation between the samples. This variation is unlikely to stem from the drying method itself, since the primary drying stage was not designed to standardize moisture content or water activity across methods, but rather to reach a comparable sensory endpoint, as judged by experienced pastırma masters consistent with how pastırma remains a largely artisanal product whose drying is traditionally guided by sensory assessment rather than a fixed physicochemical target (Batman et al., 2025).

Reaching this sensory endpoint did not equalize moisture content or water activity across methods: the shorter drying duration and higher relative humidity applied during CC and IR relative to the seven-day OA process left CC and IR samples comparatively moister, while OA samples developed a moister core beneath a drier surface, consistent with case hardening under prolonged open-air exposure. These differrences in moisture content, water activity, and matrix density established during primary drying likely influenced the diffusion and retention of cemen paste-derived compounds within the meat tissue, offering a more plausible explanation for the observed variability in sulphur compounds than drying method alone. Hazar et al. (2019) identified 12 sulfur compounds in pastirma, primarily allyl methyl disulphide and dimethyl disulfide, and reported that their concentrations varied significantly depending on processing conditions. Demirok et al. (2013), on the other hand, reported that diallyl disulphide was the volatile compound exhibiting the greatest variability in traditional pastirma, with its concentration varying widely depending on the processing conditions.

Principal Component Analysis (PCA) of volatile compounds

A Principal Component Analysis (PCA) was performed to evaluate the similarities and differences in the volatile compound profiles of the samples. PC1 and PC2 explained 40.5% and 21.7% of the total variance, respectively, for a cumulative total of 62.2%. Fig. 6A shows that the six pastirma samples were clearly separated along the first two principal components, indicating that the drying method played a more dominant role in sample clustering than muscle type. The OA and IR-L groups clustered on the negative side of PC1 and the positive side of PC2. In contrast, the IR-R sample was positioned at a high positive value on PC1, clearly distinguishing itself from all the other samples. The CC-L and CC-R samples separated in the negative direction along the PC2 axis.

Fig. 6B represents 62.1% of the total variance across 40 major volatile compounds and reveals the relationship between specific chemical groups and drying methods. On the negative side of PC1, the predominant compounds were oxidation-derived aldehydes, including heptanal, octanal and benzaldehyde, as well as 1-octanol. On the positive side, they were associated with 2-heptanone, undecane and certain aromatic hydrocarbons (benzene derivatives). OA samples showed a strong correlation with oxidation products, such as 1-octanol, heptanal, octanal and benzaldehyde. These were positioned in the upper right quadrant. In contrast, CC samples were located on the left side of the biplot, reflecting a distinctly different volatile composition.

IR-dried samples clustered in the lower quadrant, characterised primarily by 2-heptanone, undecane and certain aromatic hydrocarbons. This spatial distribution clearly demonstrates the significant impact of the drying method on the volatile profile.

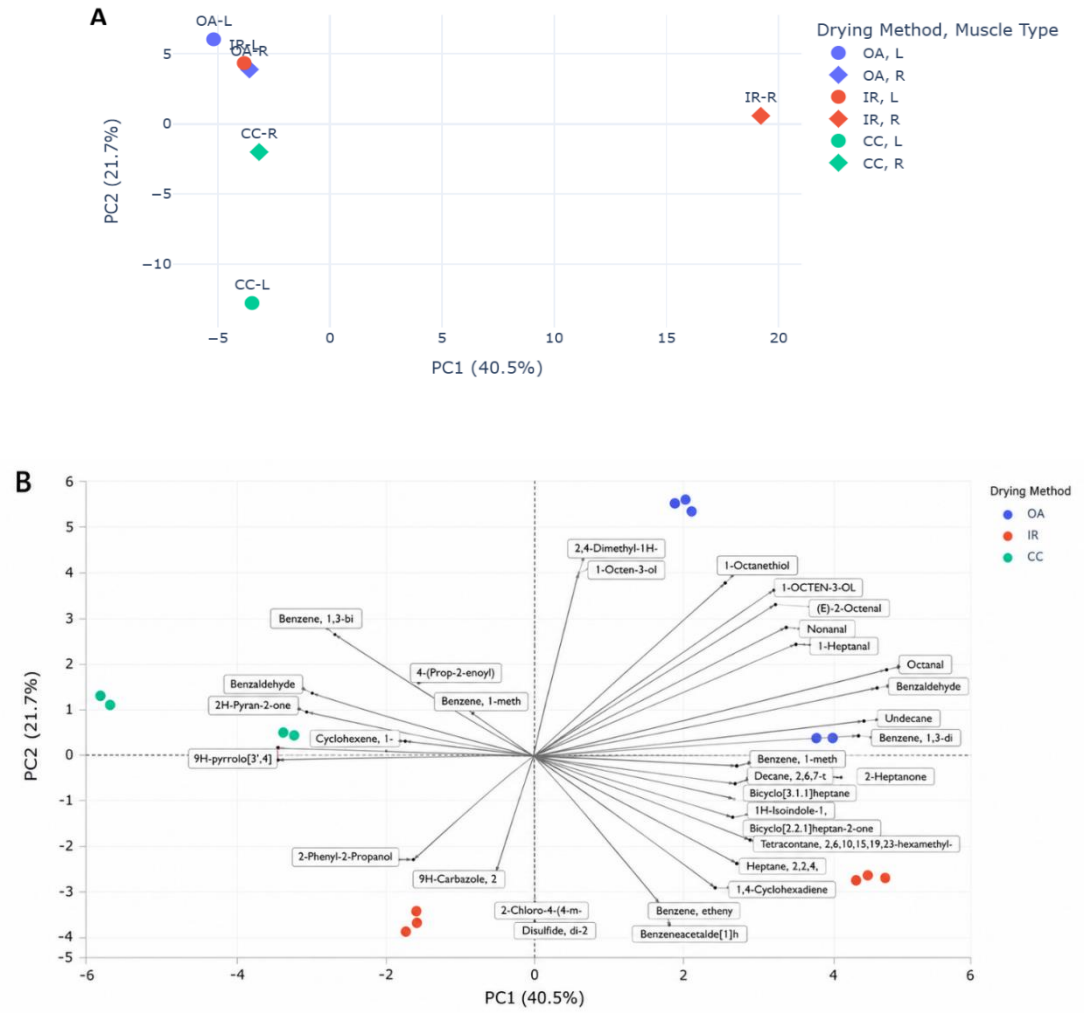


Figure 6. Principal component analysis (PCA) of volatile compound profiles in pastirma samples. A: Score plot showing the distribution of samples along PC1 and PC2, with a cumulative explained variance of 62.2%. B: This PCA biplot shows the distribution of the 40 main volatile components according to the drying method used. The vectors represent the volatile components and the dots represent the drying groups (OA, IR and CC). Muscle types: loin (L) and round (R). Drying methods: open-air drying (OA), climate-controlled chamber drying (CC), and infrared drying (IR)

The clustering of OA and IR-L samples in the negative region of PC1 is consistent with the presence of compounds derived from lipid oxidation, such as octanal and aliphatic hydrocarbons, which reach high concentrations in these samples. The separation of the CC-L and CC-R samples reflects the distinct volatile compound pattern formed by this method. The negative PC2 positioning of terpenes derived from cement paste (limonene, γ-terpinene, and β-pinene) indicates that these compounds are characteristic of the OA-L, OA-R, and IR-L samples and can be considered marker compounds that distinguish between these drying methods (Hazar et al., 2019; Kaban, 2009). The isolation of the IR-R sample at a high positive PC1 value suggests that its unique volatile profile is characterised primarily by 2-heptanone and long-chain aromatic compounds. PCA has been reported to explain 60–80% of the total variance in dry-cured meat products, and the 62.2% ratio obtained in the present study is consistent with this range (Ramirez & Cava, 2007; Li et al., 2021).

CONCLUSIONS

In conclusion, this study comprehensively investigated the effects of three different drying methods open-air drying (OA), infrared drying (IR) and climate-controlled chamber drying (CC) on the volatile aroma profile of pastirma produced from loin and round muscle, using the HS-SPME-GC/MS method during the primary drying stage. A total of 183 volatile compounds

were identified, with aldehydes, terpenes and hydrocarbons being determined as the dominant chemical classes.

The effect of the drying method on the volatile profile was found to be statistically highly significant. The significantly higher aldehyde fraction, particularly of hexanal, nonanal and octanal, in OA and IR samples compared to CC samples, suggests that these methods generate a more intense environment for lipid oxidation. Heptanal was only detected in OA, and IR-L samples, and not at all in CC samples. In terms of the terpene profile, d,l-limonene was the dominant component in all samples except the CC-R sample, with the highest concentrations found in the OA-L and IR-L samples. This suggests that the moisture content and surface properties formed during primary drying affect the diffusion and retention of terpene compounds during subsequent drying with cemen paste. Principal component analysis (PCA) differentiated the samples significantly according to drying method; PC1 and PC2 explained 62.2% of the total variance. The effect of muscle type (loin or thigh) on the volatile component profile was not statistically significant. This clearly shows that the drying method is a much more decisive factor than muscle type in determining the volatile components of pastirma. Overall, climate-controlled chamber drying produced a more consistent and controlled volatile profile, whereas open-air and infrared drying methods encouraged the development of a richer and more diverse aroma repertoire.

Further research is recommended, including the creation of sensory evaluation panels, the utilisation of experimental designs with larger replications, and the incorporation of TBA (thiobarbituric acid) analysis to enable a more comprehensive and in-depth examination of the aroma components, particularly in relation to oxidative changes and their impact on volatile profile stability. In addition, instrumental evaluation of colour parameters, along with the correlation between colour measurements and thiobarbituric acid reactive substances (TBARS) values, should be considered in future work, as this may provide important insights into product characterisation.

SUPPORTING INFORMATION

Additional Supplementary material may be found in the online version of this article.

Table S1. A total of 183 volatile compounds identified in six pastrami samples determined by HS-SPME-GC/MS analysis with HP-5MS column, alongside spectral libraries

AUTHOR CONTRIBUTIONS

Investigation, Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing-review and editing, S.G.B.

DATA AVAILABILITY STATEMENT

Data contained within the article.

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CONFLICT OF INTEREST

The author declares no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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UTICAJ NAČINA SUŠENJA NA PROFIL ISPARLJIVIH JEDINJENJA U TURSKOJ PASTIRMI

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Sažetak: U standardnoj proizvodnji pastirme, faza sušenja predstavlja najduži i najmanje kontrolisan korak. Ova studija je ispitivala infracrveno (IR) sušenje i sušenje u komori sa kontrolisanom klimom (CC) kao alternativne postupke u odnosu na sušenje na otvorenom (OA), sa ciljem skraćenja vremena prerade i procene uticaja na profil isparljivih jedinjenja. Pastirma dobijena iz dva tipa mišića (file i but) analizirana je metodom HS-SPME-GC/MS, pri čemu je identifikovano 183 jedinjenja raspoređenih u deset hemijskih klasa. OA i IR sušenje su proizveli značajno veće frakcije aldehida u poređenju sa CC sušenjem ($p < 0.001$), pri čemu je heksanal bio dominantan marker oksidacije lipida. Limonen poreklom iz čemen paste detektovan je u svim uzorcima. Analiza glavnih komponenti (PCA) je pokazala da metoda sušenja predstavlja primarni faktor varijacije volatilnog profila, dok tip mišića nije imao značajan uticaj ($p > 0.05$). IR sušenje je za kraće vreme postiglo uporedive volatilne profile sa OA sušenjem, dok je CC sušenje minimizovalo neželjene arome nastale oksidacijom, omogućavajući standardizaciju proizvoda.

Ključne reči: *suvomesnata prerađevina, infracrveno sušenje, komora sa kontrolisanom klimom, aroma, oksidacija lipida, SPME-GC/MS*

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