Use of oil mixture emulsion hydrogels as partial animal fat replacers in dry-fermented foal sausages

Aurora Cittadini [a,b], Rubén Domínguez [b], Paulo E. S. Munekata [b], Mirian Pateiro [b], María V. Sarriés [a], José Manuel Lorenzo [b,c*]

[a] Instituto de Innovación y Sostenibilidad en la Cadena Agroalimentaria (IS-FOOD), Universidad Pública de Navarra (UPNA), Campus de Arrosadia, 31006 Pamplona, Spain
[b] Centro Tecnológico de la Carne de Galicia, Avd. Galicia No. 4, Parque Tecnológico de Galicia, 32900 San Cibrao das Viñas, Spain
[c] Universidade de Vigo, Área de Tecnología de los Alimentos, Facultad de Ciencias de Ourense, Universidad de Vigo, 32004, Ourense, Spain

***Corresponding author email**: jmlorenzo@ceteca.net

Abstract

This study aimed to evaluate the influence of partial replacement of animal fat by oil mixture emulsion hydrogels on the quality properties of dry-fermented foal sausages. Three batches were elaborated: control (CON) – 100% of pork fat; treatments 1 and 2 (T1 and T2) – 50% of pork fat was replaced by oil mixture emulsions, tigernut (T1) or sesame oils (T2) blended with algal oil. Lipid reformulations reduced ($P < 0.001$) fat (36.91% *vs*. about 30%, for CON and reformulated samples, respectively), and moisture contents (33.57% *vs*. about 28%, for CON and reformulated samples, respectively), while darker sausages were obtained. These changes in the both, fat and moisture contents, have an important influence on the texture parameters, since reformulated samples presented higher values of hardness (283-317 N) than control samples (152 N). Both oil emulsion hydrogels favored a decrease ($P < 0.001$) of saturated fatty acids (34.16 *vs*. 30 g/100 g of fat), an increase ($P < 0.001$) of mono- (T1) and polyunsaturated (T2) fatty acids (depending on the batch), and an improvement of all health indices as omega-6/omega-3 (n-3/n-6) and polyunsaturated fatty acids/ saturated fatty acid ratios (PUFA/SFA), atherogenic (AI) and thrombogenic (TI) indices and hypocholesterolaemic/hypercholesterolaemic ratio (h/H). T2 seemed to reduce ($P < 0.001$) the lipid oxidation in the samples, while T1 presented the highest values. On the other hand, the terpenes and terpenoids were the most abundant volatile compounds (VOCs) found in all sausages, mainly due to the use of pepper as flavoring spice. Several differences were observed on the content of different individual VOCs (hydrocarbons, acids, alcohols, aldehydes, etc.) and also in the total VOCs content, due of both, differences in lipid oxidation processes (in accordance with TBARS values) and also the moisture and fat content of the samples. Nevertheless, consumer acceptability resulted to be unaffected (T1) or improved (T2) by the fat reformulation. Thus, overall results pointed out that the use of T2 emulsion hydrogel as a partial animal fat replacer could be a promising strategy to achieve healthier dry-cured foal sausages with high consumers’ approval.

Keywords: Lipid reformulation; Foal meat product; Healthy dry-cured sausages; Nutritional value; Volatile compounds; Sensory analysis

1. Introduction

Over the last decades, the development of healthier meat products has become one of the central issue for the scientific community and meat industry to satisfy the market requirements. Actually, modern consumers focus their attention on the quality of food and especially on its potential health effects (Teixeira & Rodrigues, 2021). In this context, meat products are generally indicated for their elevated fat contents, mostly saturated fatty acids (SFA), cholesterol and other components that could have a negative impact on human health, favoring the onset of obesity, cardiovascular problems and other chronic diseases (Nacak et al., 2021). Dry-fermented sausages are popular meat products worldwide and are particularly appreciated owing to their convenience and unique features and aromas developed during the ripening phase (Flores & Piornos, 2021; Franco et al., 2020). Nevertheless, in order to preserve these peculiarities, animal fat (generally pork back fat), rich in fat and especially in saturated fatty acids, is commonly employed in this type of products since it is essential to favor the correct dry-ripened process and as a consequence to obtain the typical technological and sensorial properties of these sausages (Utrilla et al., 2015). Moreover, the use of pork back fat reduces the production costs, considering its low economic value. Therefore, dry-fermented sausages are characterized by high fat contents, among a 40-50%, and as a result have acquired a negative connotation from the health standpoint, as the others meat products (Lorenzo & Franco, 2012).

In this sense, fat reduction and the improvement of lipid composition represents one of the leading strategy adopted in investigation with the aim of enhancing the quality of meat products (Teixeira & Rodrigues, 2021). In this regard, different options have been assayed to limit the use of animal fat and the use of healthier lipid sources (vegetable or marine oils) as its substitutes demonstrated to be a promising solution, favoring a significant reduction of both fat and SFA contents in meat products (Domínguez, Bohrer, et al., 2021). The incorporation of oils can be carried following three main ways, which found application also in dry-fermented sausages. Concretely, distinct works explored fat reduction in these products using oleogels (Franco et al., 2020; Pintado & Cofrades, 2020), microencapsulated oils (Lorenzo et al., 2016b) and hydrogels (Alejandre et al., 2016; Pintado & Cofrades, 2020; Vargas-Ramella et al., 2020). Nevertheless, recent investigations highlighted that the use of emulsion hydrogels presents several leverages in comparison with the other two techniques (Domínguez, Bohrer, et al., 2021; Domínguez, Munekata, et al., 2021). Moreover, it was pointed out that the optimization of the nutritional profile of the final products can be achieved using oils combinations instead of pure oils, moderating its potential effects at technological or sensorial levels (Rubén Domínguez, Bohrer, et al., 2021). As a result, oil mixtures structured in emulsion hydrogels are suggested as potential partial animal fat replacers in dry-fermented foal sausages. The preparation of the hydrogels is inexpensive and simple, and requires only two steps: the formation of a stable oil-in-water emulsion (composed of the oil mixture and water) and its successive gelation by structuring agents (Domínguez, Munekata, et al., 2021). In detail, in this study, alginate-based emulsion hydrogels were elaborated using algal oil mixed with tigernut or sesame oils. Algal oil is recognized for its high contents in long-chain omega-3 fatty acids (LC *n*-3), as eicosapentaenoic (EPA, C20:5*n*-3) and docosahexaenoic (DHA, C22:6*n*-3) acids (Gayoso et al., 2019). Tigernut and sesame oils represent underused dietary fat sources: tigernut is particularly rich in monounsaturated fatty acids (MUFA), like oleic acid (Sabah et al., 2019) while in sesame oil polyunsaturated fatty acids (PUFA) (mostly linoleic acid) and MUFA (mainly oleic acid) represent the predominant fractions (Matthäus & Özcan, 2018).

Besides, the selection of meat of lean species and with a valuable nutritive profile could complement the "mission" of meat industry. In this sense, horse meat in fact represents a favorable alternative for use as raw material in the preparation of healthy dry-fermented sausages considering its low fat content and "beneficial" fatty acid profile, among others attributes (Belaunzaran et al., 2015; Jastrzębska et al., 2019). In addition, equine meat is generally defined eco-friendly (Belaunzaran et al., 2015), satisfying the environmental concerns of modern consumers (Teixeira & Rodrigues, 2021).

Furthermore, to our knowledge, there is a scarce number of studies about the use of healthy oils as animal fat replacers in foal meat product (Cittadini, Munekata, et al., 2021), and completely absent in the case of foal dry-fermented sausages. Actually, the use of these healthy oil mixtures stabilized into alginate-wheat glucose-phosphate matrix as partial animal fat replacers for the development of healthy foal dry-fermented sausages has not been explored.

Thus, the purpose of this study was to investigate the effect of partial pork back fat replacement by healthy oil emulsion hydrogels on the composition, physicochemical parameters, nutritional profile, volatile compounds, sensory characteristics and acceptability of foal sausages. In this manner, the obtained outcomes can help to better understand the possibility of the practical use of these emulsion hydrogels in the production of healthier foal dry-fermented sausages. In the same time, this work sought to give value to this valuable and still untapped type of meat and to encourage the consumption of its derived products.

2. Materials and Methods

2.1. Elaboration of alginate-based emulsion hydrogels and fatty acid composition of fat sources

In the present study, two types of alginate-based hydrogels were processed with Prosella powder as gelling agent (Prosella VG NF4, Coli Ingredients, Mittelhausen, France) and elaborated a day before sausages manufacture following the procedure recently described by Cittadini, Munekata, et al. (2021): treatment 1 (T1) and treatment 2 (T2) hydrogels. In particular, these emulsions contained algal oil (2.25 g/100 g emulsion) mixed with tigernut (T1) or sesame oil (T2) (35.05 g/100 g emulsion). Algal oil (418.3 mg DHA/g oil), was generously provided by Solutex Corporation (Madrid, Spain). Tigernut oil was directly purchased from the company Tigernuts Traders SL (Valencia, Spain), while sesame oil (Naturgreen, Librilla, Murcia, Spain) was bought at a local store. The final proportions of these emulsions were as follows: water (56 g/100 g), algal and tigernut or sesame oil (37.3 g/100 g) and the Prosella powder (6.7 g/100 g). This powder consisted of jellifying agents (calcium sulphate and sodium alginate), wheat glucose syrup (7.4%), a stabiliser (disodium diphosphate, added P_2O_5: 9.58%) and an antioxidant (sodium ascorbate), which maintain oils in its structure. Table 1 shows the fatty acid composition of the fat sources used in this work.

2.2. Manufacture of dry-fermented sausages

Three different batches of dry-fermented sausages were manufactured (Figure 1): control (CON) – containing 100% of pork back fat as fat source (18.2 g/100 g) and other two experimental batches in which 50% of animal fat (9.1 g/100 g) was replaced by the alginate-based hydrogels (9.1 g/100 g) consisting of algal oil mixed with tigernut oil (T1) or sesame oil (T2), depending on the batch. All batches were formulated with the same ingredients, except for fat source as above described. In particular, the foal sausages included lean meat from Burguete foals (74 g/100 g) provided by Cárnicas Mutiloa (Rocaforte, Navarre, Spain), pork back fat purchased in a local meat industry (Cárnicas M. Boo, S.L., San Cibrao das Viñas, Ourense, Spain), water (3.2 g/100 g) and the "542 Salchichón" supplement (Laboratorios Ceylamix, Valencia, Spain) (4.6 g/100 g), containing, in unknown proportions, sugar (lactose, sucrose), salt, dextrin, spices (black and white pepper and nutmeg), milk protein, monosodium glutamate (E621), phosphates (E450 and E451), sodium erythorbate (E316), potassium nitrate (E252) and coloring (E120). No starter cultures were added. The three treatments were elaborated following the same manufacturing process. Briefly, the lean foal meat was ground using a 12 mm diameter mincing plate (Ak-Ramon Top-114, Vilassar de Dalt, Barcelona, Spain) while the fat sources were minced through a stainless-steel grinder plate of 8 mm diameter in a refrigerated mincer machine (La Minerva, A/E 22R, Bologna, Italy). Successively, all ingredients were vacuum mixed using a kneader-mixer machine (Mainca, RM-20, Granollers, Barcelona, Spain) for 2 min and maintained at 4 °C for 24 h. Then, the mix was stuffed (stuffer Sia Junior, Plegamans, Barcelona, Spain) into natural casing 35 cm long and 50-55 mm in diameter (provided by Suinca, S.L., Villamarín, Ourense, Spain), so that the final weight of each sausage was around 350 g. At this point, the sausages were kept in a fermentation chamber for one day at 20-22 °C and 80-85% of relative humidity and then transferred into a drying-ripening chamber where they were maintained for 55 days at 8-12 °C and 65-80% of relative humidity. Eight replicates were elaborated for each batch and the same manufacturing process was repeated three times, on different months (8 samples per treatment × 3 experimental treatments × 3 manufacture runs). Analyses were realized on samples taken after 55 days of ripening.

2.3. Proximate composition, physicochemical and lipid oxidation analysis

The procedures described by Lorenzo et al. (2016b) were followed for the determination of the chemical composition and physicochemical (color, pH and texture) parameters. As regards lipid oxidation, it was evaluated through thiobarbituric acid reactive substance (TBARS) index using the method reported by Tarladgis et al. (1960), and values were expressed as mg MDA/kg sample.

2.4. Fatty acids analysis

For fatty acid analysis, fat extraction and its transesterification were carried out following the protocol previously described by Domínguez et al. (2022). Separation and quantification of fatty acids methyl esters (FAMEs) were performed through the use of gas chromatography-FID technique (Agilent Technologies, Santa Clara, CA, USA), whose chromatographic conditions were formerly described (Domínguez et al., 2022) and the outcomes were expressed as g/100 g of fat. Moreover, the health indices, n-6/n-3 and PUFA/SFA ratios, atherogenic (AI) and thrombogenic (TI) indices and hypocholesterolaemic/hypercholesterolaemic ratio (h/H), were calculated as described by Cittadini, Munekata, et al. (2021).

2.5. Volatile compounds analysis

The extraction, separation, identification and determination of the volatile compounds of 1 g of sample were performed using solid-phase microextraction-gas chromatography-mass spectrometry (SPME/GC-MS) technique (Agilent Technologies, Santa Clara, CA, USA), according to the procedure and conditions described by Domínguez, Purriños, et al. (2019). The volatile results were expressed as area units of the EIC × 10^4 per gram of sample (AU × 10^4/g of sample).

2.6. Sensory analysis of foal sausages

A quantitative-descriptive analysis (QDA) was carried out in order to define the sensorial profile of the three treatments studied (CON, T1 and T2) in line with the ISO 13299: 2017 regulation (International Organisation for Standardisation, 2017a). The evaluation was conducted with a panel composed by 17 trained assessors selected from the Meat Technology Center of Galicia staff. Panelists were chosen for their sensory ability and experience in performing sensory evaluation on meat products. Moreover, before the analysis, tasters were trained following the methodology described by UNE-EN ISO 8586:2014 (International Organization for Standardization, 2014a) with the attributes and scale to employ during three sessions. Samples were individually labelled with a randomized 3-digit number and served together at room temperature on white dishes. The tasting order was designed and indicated to the panelists in order to avoid first sample and carry-over effects (Macfie et al., 1989). A total of three sessions (corresponding to each manufacture replicate) were carried out and each panelist tasted the three samples (CON, T1 and T2) in each session. In particular, nine attributes were assessed, grouped according to appearance (meat color and fat color), odor, flavor (black pepper flavor, rancid flavor and global flavor), taste and texture (hardness and chewiness). Tasters evaluated these attributes using a structured scale from 0 (sensation not perceived) to 10 (the maximum sensation).

For sensory acceptability analysis, a total of 51 consumers (29-45 years and from both genders) from Ourense (Spain) participated in the test. The World state of emergency and the approved restrictions (November 2020) limited the participation of a major number of tasters, nevertheless it was obtained an appropriate number according to Mammasse & Schlich (2014). The aim of this test was to evaluate the overall acceptability of the different sausages elaborated. Each consumer tasted the three samples, one for each formulation, in a single session. They evaluated the foal sausages employing a 7-point hedonic scale, which ranged from "1-disliked much" to "7-liked much". Moreover, it was asked to order the samples according to their preference (International Organisation for Standardisation, 2017b) using a 3-point scale (1=less favorite and 3=most favorite). Furthermore, tasters informed also their purchase intentions of the different foal sausages treatments. Samples were three-digit coded and randomly served to the assessors (Macfie et al., 1989).

The sensory evaluations were performed in the sensorial analysis laboratory of the Meat Technology Center of Galicia (Ourense, Spain) equipped with individual cabinets under white light according to UNE-EN ISO 8589:2010/A1:2014 regulation (International Organization for Standardization, 2014b). The sausages were cut into slices (5 mm thick) using a commercial slicing machine (Bizerba SE12-S, Bizerba GmbH & Co. KG, Balingen, Germany). Moreover, water and unsalted toasted bread were provided to the tasters to cleanse the palate and remove residual flavors at the beginning of session and between samples.

2.7. Statistical Analysis

The SPSS statistical software (SPSS 25.0, Chicago, IL, USA) was used to carry out all statistical analyses. Normal distribution and variance homogeneity were firstly verified applying Shapiro-Wilk and Levene tests, respectively. Data were submitted for analysis of variance (ANOVA), where the parameters were set as dependent variables, treatment (fat source) was included as fixed effect and replications (the experiment was repeated three times) were considered as random effects, meanwhile for sensory acceptance consumers were also comprised as random effect (each taster evaluate three samples, one for each treatment, in a single session). Duncan's method was employed to assess the pairwise differences between least-square means. In addition, correlations between variables ($P < 0.05$) were determined by correlation analyses using Pearson's linear correlation coefficient. Differences were considered significant if $P < 0.05$. Moreover, Friedman test with Newell and MacFarlene tables ($\alpha = 0.05$) was used to perform the statistical evaluation of the preference data. When a significant effect ($P < 0.05$) was found, least significant differences (LSD) test was employed as a multiple comparison test.

3. Results and Discussion

3.1. Physicochemical parameters of dry-fermented foal sausages

Table 2 shows the proximate composition and physicochemical results of the dry-fermented foal sausages. The use of alginate emulsion hydrogels produced a significant ($P < 0.001$) decrease of moisture, where CON samples presented the highest percentages in comparison with the reformulated sausages. Our results for CON group are in agreement with the range of values (30-

34%) published in literature for foal dry-fermented sausages (Domínguez et al., 2016; Lorenzo et al., 2012; Lorenzo & Franco, 2012). Similarly, the values of T1 and T2 groups are consistent with those found by other authors (around 25-30%) (Alejandre et al., 2016; Lorenzo et al., 2016b; Vargas-Ramella et al., 2020), who experimented potential animal fat replacers in dry-ripened sausages. Moreover, in line with our results, other studies recorded the lowest moisture percentages in reformulated dry-fermented sausages, where pork back fat was partially replaced by encapsulated fish oil-in-konjac matrix (Lorenzo et al., 2016b), vegetable oils (olive, canola and soy oils) structured in emulsion hydrogels (Vargas-Ramella et al., 2020) or linseed oil sterols-based oleogel (Franco et al., 2020). On the contrary, some authors observed an opposite trend (Alejandre et al., 2016; Franco et al., 2020; Pintado & Cofrades, 2020). It is recognized that the drying-ripening process play a key role for the gradual and suitable dehydration of this type of product. Hence, the discrepancies detected between studies could be associated to different factors, as the characteristics of the product (type of meat, percentage of fat, casing size, etc.) as well as the distinct ripening conditions (temperature, time, air speed, relative humidity, etc.) or the behavior of the various fat substitutes (encapsulated oils, emulsions or oleogels, etc.) (Vargas-Ramella et al., 2020). Considering our outcomes, it could be assumed that sausages with animal fat replacement presented a faster drying process giving rise the moisture differences among CON and the experimental batches. Actually, it is well known that animal fat creates a barrier and diminishes water loss during the drying step. Conversely, the emulsion hydrogels employed for the elaboration of T1 and T2 samples contain a 56% of water, which promoted the drying process. Consequently, it is evident that emulsion hydrogels present a scarce barrier effect in comparison with animal fat. However, this apparent flaw could represent an important advantage for the producer. In fact, owing to a faster and intense drying process, the manufacturing time of the reformulated sausages could be significantly shorter than a conventional production process and consequently it implies technological and economic benefits (Vargas-Ramella et al., 2020). Furthermore, other parameters as texture and sensorial characteristics could be affected by the changes in the final moisture between CON and the reformulated batches.

Considering the fat content (on a dry matter basis), also in this case, the use of the oil emulsion hydrogels favored a significant (P < 0.001) reduction. Actually, treatments achieved a diminution of about 18% (T1) and 17% (T2) compared with control group. This diminution could be expected taking in consideration that pork back fat, containing about 80% of total fat (Vargas-Ramella et al., 2020), was replaced for oil-in-water emulsions which only consisted of 37.2% oil. These fat changes are supported, in fact, by other authors, who employed gelled oils to reformulate other analogous dry-ripening sausages, such as fuet (Pintado & Cofrades, 2020), salchichón (Franco et al., 2020; Lorenzo et al., 2016b) and other types of dry-fermented sausages (Alejandre et al., 2016; Vargas-Ramella et al., 2020). Besides, our outcomes are close to those obtained in previous studies (Fonseca et al., 2015; Vargas-Ramella et al., 2020).

On the other hand, protein values (on a dry matter basis) were not significantly (P > 0.05) affected by sausages reformulation, being similar among the three batches. Although the same quantity of meat was employed for the elaboration of all batches, this behavior could be related to the fact that pork backfat protein had a minimal impact on the reformulation of dry-fermented sausages (Lorenzo et al., 2016b). The same behavior in fact was also noted in studies about reformulated pork dry-cured sausages (Alejandre et al., 2016; Lorenzo et al., 2016b; Stajić et al., 2014).

In contrast, the pork fat partial substitution significantly (P < 0.001) enhanced the ash content. A similar trend was reported by other authors (Lorenzo et al., 2016b; Pintado & Cofrades, 2020), who studied dry-fermented sausages formulated with healthier oils. These differences could be justified by the decrease in fat amount (Vargas-Ramella et al., 2020). Moreover, according to recent studies (Barros et al., 2020; Vargas-Ramella et al., 2020), the variation in the ash content may be due to the amount of Prosella powder (6.7 g/100 g) used to prepare T1 and T2 emulsions.

In addition, the incorporation of oil emulsion hydrogels showed a significant (P < 0.05) effect on instrumental color data. In particular, the reformulated batches were darker (P < 0.001) than CON group, following the same tendency observed in healthy pork and deer dry-cured sausages (Lorenzo et al., 2016b; Pintado & Cofrades, 2020; Vargas-Ramella et al., 2020). Actually, the greatest L* values were detected in CON samples, followed by T1 and T2. The reduction of animal fat could be considered responsible for the lightness diminution in the reformulated batches, since this fat is white and it supplies the brilliant aspect of sausages (Lorenzo et al., 2016b). In fact, it is widely known that the fat content highly affects L* values, since as the fat amount in sausages increases, the L* values also are higher (Fonseca et al., 2015). A positive and significant correlation was actually found between these two variables (r=0.655, P < 0.001). Moreover, Fonseca et al. (2015) affirmed that L* values significantly diminished during ripening, probably owing to the water loss. Thus, another possible explanation of our outcomes is that the greater and faster dehydration process during ripening of the experimental sausages led to lower L* values. Indeed, a significant positive correlation was detected between L* and moisture values (r=0.767, P < 0.001). As regards data obtained for a* index, CON and T2 samples showed similar (P > 0.05) values, while T1 sausages presented the lowest (P < 0.001) red hue. Vargas-Ramella et al. (2020), who investigated the use of healthy oil as potential pork back fat replacers in dry-cured deer sausages, detected a tendency similar to ours. Actually, they found that olive and canola oils did not affect the redness of the product, while sample containing soy oil emulsion hydrogels showed a significant decrease of a* values. Thus, it could be concluded that, depending on the type of oils employed, the substitution of animal fat for oil-in-water stabilized in Prosella gel represents a promising strategy, since it is able to give rise products that preserve the typical red color of sausages. In this sense, our data indicated that the combination of algal oil with sesame oil demonstrated to be a better solution than mixing with tigernut. Finally, as for lightness (L*), also b* values showed a significant ($P < 0.01$) decrease in both reformulated batches. In particular, T1 and T2 samples showed similar values, while CON group reported the highest values. These findings are in agreement with those reported by other investigators (Lorenzo et al., 2016b; Vargas-Ramella et al., 2020), who observed that the use of healthy oils as fat replacers in dry-fermented sausages produced a decrease in yellowness hue. Whereas, some studies reported that the b* values of the final product increased (Franco et al., 2020; Pintado & Cofrades, 2020) or were not affected (Lorenzo et al., 2016b) by the replacement of animal fat for oil incorporated in emulsion, oleogel or encapsulated form. Nevertheless, with all results in mind, it is evident that factors such as the typical color of the emulsifiers or oleogelators as well as of the oils employed for the gel elaboration, the amount of oil used in the emulsion or the oleogel and the ingredients employed for the meat product elaboration can be at the base of the distinct results published in literature (Vargas-Ramella et al., 2020). For instance, Franco et al. (2020) observe higher b* values in sausages formulated with beeswax linseed oleogel and justified this fact to the yellow color of both beeswax and oil. In the same manner, lower yellowness hue was observed in foal burgers reformulated with an emulsion hydrogel containing a mix of pumpkin seed and algal oils and this finding was related to the characteristic greenish color of the pumpkin seed oil (Cittadini, Munekata, et al., 2021).

Conversely, the pH values did not present significant differences ($P > 0.05$) among batches and the outcomes obtained were comparable with those published in literature (Franco et al., 2020;

Vargas-Ramella et al., 2020). In agreement with our results, also other studies (Alejandre et al., 2016; Fernández-Diez et al., 2016) reported that animal fat replacement in sausages did not affect pH values. Furthermore, it is worth noting that our values were less than 5.30 due to the fermentation process and the acidification caused by lactic acid bacteria (Muguerza et al., 2002; Ockerman & Basu, 2014), increasing and ensuring the microbiological stability of the final product.

Besides, statistical analysis showed that the fat replacement had a significant effect on the textural parameters. In particular, the reformulated batches recorded higher ($P < 0.001$) values for hardness, gumminess and chewiness in comparison with CON samples, T2 reported the lowest ($P < 0.05$) values for springiness, while cohesiveness resulted to be the unique parameter unaffected ($P > 0.05$) by the reformulation. In agreement with our results, different works (Lorenzo et al., 2016b; Lorenzo & Franco, 2012), in fact, noted that greater was the fat reduction, harder structures were obtained. Vargas-Ramella et al. (2020) also observed a significant increment of hardness, gumminess and chewiness in reformulated deer dry-cured ~~deer~~ sausages. Whereas, Pintado & Cofrades (2020) published that the use of the mixture of olive and chia oil in oleogel or emulsion forms diminished the hardness of fuet. A similar result was obtained by Jiménez-Colmenero et al. (2013) using a healthy oil combination stabilized in konjac matrix as animal fat replacer. In this latter case, this discrepancy could be related to the different criteria employed to define the end of the ripening process, which was established on the base of the level of weight loss (and not of the ripening time). Additionally, the observed differences could be related to the moisture content (Fonseca et al., 2015). In fact, it is widely known that the dehydration process during ripening and as a consequence the final moisture content have a crucial role in the textural features of this type of product (Vargas-Ramella et al., 2020). Actually, moisture content resulted to be negatively correlated with hardness (r=-0.747, P = < 0.001), gumminess (r=-0.702, P = < 0.001) and chewiness (r=-0.662, P= < 0.001) values, in line with our findings.

Furthermore, data indicated that the type of fat source had a significant (P <0.001) influence on lipid stability of the dry-fermented foal sausages (Figure 2). In particular, T2 samples (1.42 mg MDA/kg sample) recorded the lowest values for lipid oxidation, followed by CON (3.12 mg MDA/kg sample) and T1 (5.06 mg MDA/kg sample) sausages. Among them, the sausages belonging to the group reformulated with T2 emulsion hydrogel were the unique showing values below sensory threshold limit of 2.0 MDA/kg sample (Campo et al., 2006; Lorenzo et al., 2016b). Contrasting results are present in literature, in fact, TBARs values resulted unaltered when linseed oil gelled emulsion was employed as pork fat replacer (Alejandre et al., 2016) in dry-fermented sausages. While, lipid oxidation increased using encapsulated fish oil in konjac matrix (Lorenzo et al., 2016b). In this context, the increase of TBARs values in reformulated meat products is generally justified by the presence of the high contents of unsaturated fatty acids (UFA) which are more susceptible to the oxidative degradation (which can lead to rancidity) than SFA. This fact could explicate the results for T1 batch. Although, Barros et al. (2020) observed a significant reduction of TBARs values in burger reformulated with tigernut emulsion hydrogels. However, in this study, the elevated TBARs values observed in T1 sausages could be related to the fact that this oil and its combination with algal oil is not suitable to be incorporated in dry-fermented sausages, since it could be possible that the presence of the marine oil reduces the oxidative stability of tigernut oil or that the dry-curing process could alter the oils properties. Thus, considering the tigernut oil, it could be preferred its application in fresh meat products, where were detected better results (Barros et al., 2020). On the other hand, T2 group, despite of the high concentration of UFAs, reported an opposite trend. Our outcomes could be related to different factors, as the presence of high amounts of natural antioxidants in the sesame oil, the protective action of the emulsion as well as the food matrix studied, among others (Alejandre et al., 2017; Moghtadaei et al., 2018). Indeed, some authors (Andargie et al., 2021; Matthäus & Özcan, 2018) affirmed that sesame oil is characterized by an elevate oxidative stability thanks to the presence of huge amounts of lignans, including sesamin and sesamolin, among others antioxidant compounds.

3.2. Fatty acids composition of dry-fermented foal sausages

The effect of the partial replacement of pork backfat by T1 and T2 emulsion hydrogels on the fatty acids content (g/100 g of fat) of dry-fermented foal sausages is displayed in Table 3. Unsurprisingly, the use of the alginate emulsion hydrogels as animal fat replacers significantly affected the lipid profile of sausages ($P < 0.05$). As shown, in all formulations MUFA represented the predominant group, followed by SFA and finally PUFA (MUFA > SFA > PUFA). Whilst, considering the individual fatty acid amounts, the majority was represented by the oleic (C18:1*n*-9), followed by palmitic (C16:0), linoleic (C18:2*n*-6) and stearic (C18:0) acids (C18:1*n*-9 > C16:0 > C18:2*n*-6 > C18:0). Our results seem to corroborate those published in recent studies about reformulated pork (Franco et al., 2020; Lorenzo et al., 2016b) and deer (Vargas-Ramella et al., 2020) fermented sausages.

As regards SFA, it was observed a significant ($P < 0.001$) reduction of their contents in reformulated samples, about an 11-12% less in comparison with CON group. Our outcomes could be justified by the significant lower contents of C16:0 and C18:0 obtained in the reformulated batches (due to significant lower amounts of these fatty acids in the tigernut and sesame oils; Table 1). Therefore, the SFA diminution was accompanied also by a decrease of the atherogenic, hypercholesterolaemic and thrombogenic (C16:0 and C18:0) effects (Fernández et al., 2007; Montesano et al., 2018).

MUFA content also resulted to be influenced by the type of fat source employed ($P < 0.001$) and the concentrations changed among the batches. In particular, samples belonging to the T1 group recorded the highest ($P < 0.001$) values in comparison with the CON and T2 groups, which conversely presented similar values. In fact, as shown in Table 3, T1 samples reported also the major ($P < 0.001$) values for C18:1*n*-9 (the most abundant fatty acid in tigernut oil). This trend was also found in previous studies, where olive and canola (Vargas-Ramella et al., 2020) or peanut and linseed (mixed) (Nacak et al., 2021) oil emulsion hydrogels were experimented as fat replacers in sausages.

Furthermore, statistical analysis showed significant ($P < 0.001$) differences in PUFA contents among treatments. In comparison with CON sausages, T2 group showed the highest values while T1 one the lowest amounts. Actually, although the linoleic acid (C18:2*n*-6) represented to be the most abundant PUFA in the three formulations, it is predominant ($P < 0.001$) in T2 samples. This fatty acid showed in fact high concentrations in sesame oil, as shown in Table 1, which can also explicate the highest ($P < 0.001$) amounts of omega-6 (*n*-6) in T2 sausages. Similarly, considering omega-3 (*n*-3) fatty acids, T2 group showed also the greatest ($P < 0.001$) concentrations of α-linolenic acid (C18:3*n*-3). Additionally, the reformulated dry-fermented sausages reported, in general, a significant ($P < 0.001$) increase of the total amounts of *n*-3, favored by the use of algal oil in the emulsion hydrogels. Indeed, as above commented, it is recognized that marine oils are valuable sources of LC *n*-3, as EPA and DHA (Gayoso et al., 2019). This is also confirmed by our data, where T1 and T2 samples showed a remarkable ($P < 0.001$) increment of LC *n*-3 contents in comparison with CON group. In particular, the modified sausages contained 130.49 mg EPA+DHA/100 g of product (T1 samples) and 155.15 mg EPA+DHA/100 g of product (T2 samples) (data not shown). Hence, our reformulated batches could be claimed as "source of omega-

3 fatty acids" and "high omega-3 content" in line with the European Parliament regulation (EC, 2006), which states that products with a minimum of 40 and 80 mg of the sum of EPA+DHA per 100 g of product can be included in these categories, respectively.

On the whole, our results are consistent with those published by some authors (Franco et al., 2020; Pintado & Cofrades, 2020; Vargas-Ramella et al., 2020), who also found a significant reduction of SFA concentrations and an increment of MUFA and/or PUFA values investigating the use of oil-in-water emulsions as pork backfat replacers in dry-fermented sausages. Furthermore, according to our outcomes, they observed an increase in *n*-6 and/or *n*-3 fractions on the base of the oils employed. Nevertheless, multiple factors can affect the intensity of this effect, such as the amount of animal fat substitution (partial or total), the percentage of oil employed in the emulsion and the type of oil selected for the sausage elaboration (Vargas-Ramella et al., 2020). Henceforth, as a general conclusion, it seems that the fatty acid composition of the fat source used in our formulations are reflected in the lipid profile of the dry-cured sausages. Thus, the differences in fatty acids discussed above are related to the oil composition.

Finally, in relation to the nutritional values of foal sausages, taking in consideration the variation of *n*-3 and *n*-6 fatty acids, the inclusion of the emulsion hydrogels in sausages significantly decreased ($P < 0.001$) the *n*-6/*n*-3 ratio, which is considered an important health parameter. It is well-known that unbalanced diets with high values of this ratio, are normally associated with an increased incidence of developing severe pathogenesis as cancer and inflammatory diseases, depressive disorders and cardiovascular illness (Lorenzo et al., 2016b; Marventano et al., 2015), whereas the consumption of products rich in *n*-3 PUFA demonstrates to play a protective role against these diseases (Pourashouri et al., 2014; Vargas-Ramella et al., 2020). In particular, in line with the nutritional recommendations, this parameter should be minor than 4

(Simopoulos, 2004), being the ideal value 1 (Marventano et al., 2015). In our study, T1 batch was the unique formulation with values below 4, while CON and T2 samples presented higher (P < 0.001) values than those recommended. Other investigations showed a significant decrease of this ratio in dry-fermented sausages reformulated with linseed (Franco et al., 2020) or with olive oil mixed with chia (Pintado & Cofrades, 2020) or with linseed and fish (Jiménez-Colmenero et al., 2013) oils, presenting values lower than 4. On the other hand, Vargas-Ramella et al. (2020), who studied the inclusion of gel emulsions containing olive, canola or soy oils in our same product, also noted a diminution of the n-6/n-3 values in reformulated samples but not enough to be within the range recommended. Nevertheless, it is important to highlight that the results obtained from this ratio should not be considered alone. The use of T1 and T2 emulsion hydrogel enhanced the PUFA/SFA ratio. In fact, in comparison with the conventional sausages, both reformulated samples recorded a significant (P < 0.001) increase of this ratio, reaching values above 0.45 (0.52 in T1 and 0.73 in T2), as recommended (Wołoszyn et al., 2020). Therefore, these findings indicated that the reformulation of foal dry-cured sausages improved the nutritional characteristics of the fatty acid composition. Besides, the partial substitution of pork fat by the emulsion hydrogels provided a significant (P < 0.001) diminution of atherogenic (AI) and thrombogenic (TI) indices and a significant (P < 0.001) increase in h/H index in comparison with CON samples, evidencing also in this case the enhancement of the lipid profile of T1 and T2 groups. Thus, our results agree with the recommendations, which affirmed that the healthy products should have AI and TI values as low as possible (Ulbricht & Southgate, 1991), whereas h/H should be high. Hence, our samples showed encouraging outcomes. In fact, this same trend was also found by other authors (Barros et al., 2020; Cittadini, Munekata, et al., 2021; Nacak et al., 2021), who applied healthy oil emulsions as fat replacers in meat products. Consequently, with all the results in mind, it is evident that T1 and T2 reformulations conferred healthier features to the final products. Moreover, algal oil, despite of its high SFA and low MUFA contents, is a valuable source of PUFA and especially of *n*-3 fatty acids, as above commented (Table 1). Hence, its combination with other healthy oils and its inclusion in the formulation of the emulsion hydrogel could be considered a successful strategy since this marine oil favored and participated to the improvement of the fatty acid profile and nutritional characteristics of our reformulated sausages.

3.3. Volatile compounds of dry-fermented foal sausages

Table 4 and Table 5 shows the effect of pork back fat partial replacement on the volatile organic compounds (VOCs) in the headspace of dry-cured foal sausages. In particular, a total of 96 compounds were identified and were grouped into eleven chemical families: hydrocarbons (7), terpenes and terpenoids (25), acids (2), alcohols (16), aldehydes (14), ketones (7), esters (13), furans (2), nitrogen compounds (5), sulphur compounds (3) and others (3).

Considering hydrocarbons, the seven substances belonging to this VOC family were detected in all treatments and distributed as follows: five lineal hydrocarbons, one branched and one cyclic hydrocarbons. As shown in Table 4, reformulation significantly ($P < 0.001$) affected the total hydrocarbons contents. A significant ($P < 0.001$) reduction was observed in T1 group, while the other two treatments showed similar values. This result is mainly due to the elevated ($P < 0.001$) amounts of total lineal hydrocarbons found in CON and T2 samples and especially to the highest ($P < 0.001$) values of pentane, representing the most abundant compound in these treatments. This compound in fact recorded values about 17-fold than those obtained by T1 group. On the other hand, T1 generated the greatest ($P < 0.001$) amounts of octane, the second most plentiful hydrocarbon identified. According to the literature, lipid oxidation reactions are the main cause of the generation of short-chain hydrocarbons (<10 carbons). Indeed, the results obtained for pentane could be explained by the fact that this VOC compound is normally associated to linoleic acid oxidation (Domínguez, Pateiro, et al., 2019). As can be seen in Table 3, in fact, CON and T2 sausages recorded also the greatest amounts of this fatty acid in comparison with T1 ones. Similarly, octane is considered a product of oxidizing oleic acid (Domínguez, Pateiro, et al., 2019). The same origin is attributed to heptane, showing the greatest amounts in T1 group (Domínguez, Pateiro, et al., 2019). Actually, this was confirmed by our data, where this fatty acid reported the highest concentrations in the sausages belonging to T1 batch (Table 3). These compounds were previously detected by other authors studying dry-fermented sausages (Alarcón et al., 2021; Domínguez et al., 2016). Moreover, in relation to the total volatile compounds content, hydrocarbons represented the fifth most abundant group for CON and T2 batches and the eighth for T1 samples. However, this VOC family is characterized by a high olfactory threshold (Flores, 2018; Zhou et al., 2020), so it could be supposed that these substances had a low impact of the aroma of our sausages.

On the other hand, terpenes and terpenoids represented the most abundant family of VOC in all formulations, recording a total percentage of 48.04% in CON samples, 57.57% in T1 sausages and 63.19% in T2 ones. This trend is in line with recent studies about Spanish sausages (salchichón), which reported that this VOC family was the predominant in this type of product (Álvarez et al., 2020; Domínguez et al., 2016; Domínguez, Purriños, et al., 2019). In particular, o-cymene showed to be the most plentiful compound in the three treatments (Table 4). This finding agree with Vargas-Ramella et al. (2020), who found the same tendency in dry-fermented deer sausages reformulated with healthy oils. Furthermore, 3-carene, D-limonene, sabinene, α-phellandrene, β-pinene, cyclophencene, safrole, β-myrcene and γ-terpinene represented, in decreasing order, ones of the most abundant terpenes detected in our samples. Several studies confirmed the presence of these compounds in pepper (Marušić, Vidaček, Janči, Petrak, & Medić, 2014; Montanari et al., 2018). Concretely, black pepper (*Piper nigrum* L.) is a popular flavoring spice and is normally added to dry-fermented sausages as additive owing to the pungency of its extracts and the aroma of its essential oils (Milenković & Stanojević, 2021). These singular compounds were in fact previously identified in other dry-fermented sausages (Alarcón et al., 2021; Álvarez et al., 2020; Domínguez, Purriños, et al., 2019) elaborated with pepper, including also low fat sausages (Fernández-Diez et al., 2016; Vargas-Ramella et al., 2020). Nevertheless, other authors (Marušić et al., 2014; Petričević et al., 2018) found some of these substances, as 3-carene, D-limonene or β-pinene in dry-ripened products elaborated without spices, concluding that these VOCs could be also related to the alimentation of the animals. Therefore, considering our results, it is evident that the spices-derived compounds dominated the aromatic profile of the sausages, whereas the substances generated from the lipid oxidation, microbial metabolism or other physicochemical modifications affected to a lesser degree on the total VOCs of this type of meat product. In particular, this family of VOCs provides lemon (citrus), fresh, menthol and herbal (herbaceous), pungent notes (Domínguez et al., 2016; Milenković & Stanojević, 2021). Moreover, as shown in Table 4, statistical analysis showed that reformulated sausages generated higher ($P <$ 0.001) individual and total amounts of terpenes and terpenoids than CON samples. The same tendency was observed by other investigators, who studied the use of cellulose gel (Campagnol et al., 2012) or healthy oils emulsions (Vargas-Ramella et al., 2020) as animal fat replacers in dry-ripened sausages. This behavior could be justified by the potential effects of fat on flavor. Indeed, fat not only may act as flavor precursor but also as solvent of these aromatic substances, delaying their liberation (Fonseca et al., 2015). Besides, the reduced moisture percentages detected in the T1 and T2 samples could be also considered the reason of their higher contents in terpenes and terpenoids (Vargas-Ramella et al., 2020). Actually, in this study, it was found that these compounds were negatively correlated with the moisture content (r = -0.685; $P < 0.001$).

As regards acids, only two compounds were identified in our samples, butanoic and hexanoic acids (Table 4), which are generally present in foal dry-cured sausages (Domínguez et al., 2016; Lorenzo et al., 2016a). On the other hand, in our samples were not detected acetic acid, which was indicated as the most abundant organic acid normally found in this type of product (Domínguez, Purriños, et al., 2019; Fernández-Diez et al., 2016). However, it is probably that this compound was subjected to a chemical transformation, as esterification. Moreover, also in this case, fat reformulation had a significant effect on the total contents of this class of compounds, where T1 samples generated the highest ($P < 0.001$) amounts in comparison to the other two batches, which showed similar values ($P > 0.05$). This result is also confirmed by the tendency of the singular volatile compounds. In fact, the use of T1 emulsion hydrogel favored the production of greater areas of both butanoic ($P < 0.01$) and hexanoic ($P < 0.001$) acids than CON and T2 sausages. In particular, in our study, butanoic acid showed to be the most plentiful in all formulations. According to the literature (Andrade et al., 2010; Lorenzo et al., 2016a), the origin of this compound is linked to the carbohydrate fermentation induced by microorganisms as lactic acid bacteria (LAB), probably occurring during the fermented stage of sausages elaboration. This organic acid, which generally gives off unpleasant fermented and cheese-like notes (Domínguez et al., 2016), is described as a potent odorant with a relevant role in the characteristic aroma of fermented sausages (Montanari et al., 2018). In fact, Domínguez, Purriños, et al. (2019) stated that low-chain acids (containing less than 6 carbon atoms/ < 6 carbons) have a significant impact on meat products aroma due to their low odor threshold values. However, considering the contribution of acids on the total volatile profile, these compounds occupied only the fifth (T1) and the sixth (CON and T2) position of the eleven families detected.

Alcohols occupies a leading role in the aroma development of dry-fermented meat products. Moreover, the pork back fat partial substitution had a significant (P < 0.001) impact on total alcohols, where reformulated sausages reported higher values than CON samples, especially T1 group, followed by T2 and CON ones (Table 4). Actually, the most plentiful alcohols detected in our samples, 2,3-butanediol, followed by benzyl alcohol, showed a similar trend. Our findings agree with those obtained by other authors (Vargas-Ramella et al., 2020), who described 2,3-butanediol as a predominant alcohol in fat-reduced sausages. This compound, providing fruity, creamy and buttery aromas, normally derives from carbohydrate fermentation (Mansur et al., 2018). Moreover, 1-penten-3-ol, glycidol, 1-pentanol, 1-hexanol and 1-octanol represented other major alcohols identified in our sausages. These compounds, together with 1-butanol or 1-propanol, are generally found in dry-fermented sausages (Alarcón et al., 2021; Vargas-Ramella et al., 2020). Previous studies reported that in fermented sausages, alcohols, particularly linear alcohols, derived mostly from lipid oxidation, being related to the reduction of their homologous aldehydes (Domínguez, Pateiro, et al., 2019; Domínguez, Purriños, et al., 2019). Concretely, in this study, it was observed that the lipid-derived alcohols recorded the lowest (P < 0.001) values in T2 sausages in comparison to the other two batches. In fact, this tendency was found in compounds as 1-penten-3-ol, 1-pentanol and 1-butanol, commonly described as products of oxidizing linoleic acid (Domínguez, Pateiro, et al., 2019; Domínguez, Purriños, et al., 2019), although T2 samples resulted to be the most abundant in this fatty acid (Table 3). Nevertheless, the presence of natural antioxidants in the oils included in T2 emulsion hydrogel (especially sesame oil) could be considered the reason of our outcomes, since they could limit the lipid oxidation in the sausages

(Andargie et al., 2021; Matthäus & Özcan, 2018). Furthermore, 1-hexanol and 1-octanol, whose origin is generally correlated to oleic acid degradation (Domínguez, Pateiro, et al., 2019) also reported the smallest (P < 0.001) areas in T2 samples and the highest in T1 ones. In this case, our findings are in line with the lipid profile of samples, where T1 resulted to be the group with the major amounts of this fatty acid, while T2 group showed the lowest concentrations (Table 3). Finally, though singular alcohols did not present a unique and clear trend, it was noted that T1 generated the highest (P < 0.001) amounts of this group of VOCs, followed by T2 and CON treatments. In addition, in this case, it was found a significant and negative correlation among moisture and total alcohols (r = -0.413; P < 0.001). Finally, it is worth highlighting that this family of compounds occupied a relevant percentage in relation to the total volatile compounds, being the fourth most plentiful group for CON and T1 samples, and the third for T2 ones. These substances actually are considered of great importance for the aroma of dry-cured meat products (Domínguez, Purriños, et al., 2019), due to their low odor threshold detection values. Concretely, some authors affirmed that these VOCs conferred woody, herbaceous, pungent, balsamic and fatty notes and also sweet, fruity or mushroom and onion like odors (Bosse (née Danz) et al., 2017; Domínguez, Purriños, et al., 2019).

The aldehydes represented the third most abundant family in relation to the total content of VOCs for CON (11.54%) and T1 (10.89%) group, while occupied the fourth position in T2 (5.01%) samples. As can be seen in Table 5, considering the singular compounds, the most abundant was hexanal for CON and T1 batches, while benzeneacetaldehyde represented the major areas for T2 one. Our findings are consistent with the results recently obtained in dry fermented sausages, where some researchers (Lorenzo et al., 2016b; Vargas-Ramella et al., 2020), found that hexanal was the main aldehyde in dry-fermented sausages, while others reported that benzenacetaldehyde was the predominant (Domínguez, Purriños, et al., 2019). Moreover, other relevant aldehydes were detected in this study, as pentanal, propanal, benzaldehyde and heptanal. According to the literature, the origin of these compounds could be related to three main routes. Lineal aldehydes are mainly considered product of the fatty acid oxidation (Domínguez, Pateiro, et al., 2019; Domínguez, Purriños, et al., 2019), branched aldehydes are derive from the amino acid degradation and proteolysis (Bosse (née Danz) et al., 2017; Domínguez, Purriños, et al., 2019), while cycloaldehydes are related to Strecker degradation of amino acids, such as phenylalanine or leucine (Vargas-Ramella et al., 2020). Among the lineal compounds, Domínguez, Pateiro, et al. (2019) stated that hexanal is a leading indicator of quality and lipid stability in meat and meat products and it could derive from multiple pathways as the oxidation of oleic, linoleic or arachidonic fatty acid. Similarly, pentanal could derive from linoleic oxidizing, while heptanal from the oleic acid deterioration processes (Domínguez, Pateiro, et al., 2019). On the other hand, propanal is associated to linolenic acid degradation (Domínguez, Purriños, et al., 2019). Considering our data, as shown in Table 5, the partial replacement of animal fat significantly affected total ($P < 0.001$) aldehydes contents, where T1 favored a significant increase of these compounds, while T2 showed an opposite tendency recording the lowest values. These results could be justified principally by the behavior of the total lineal aldehydes, representing the most abundant fraction within this family of VOCs and reporting the same trend. In fact, as regards the singular compounds, some of the most abundant aldehydes identified as hexanal, showed the predominance ($P < 0.001$) of T1 samples and the low amounts of T2 group. Similarly, other lineal and lipid-derived compounds showed the same trend, except for heptanal. Moreover, some of these outcomes are in line with the fatty acid composition of our treatments (Table 3). Concretely, T1 sausages showed also the highest contents of oleic acid, justifying the elevated generation of hexanal, heptanal and nonanal. On the contrary, although samples belonging to T2 group showed to be rich in α-linolenic and linoleic fatty acids, it was not found a relation with the related lipid-derived volatile compounds, propanal, butanal and pentanal, respectively. As previously commented, the presence of natural antioxidants and the stability of the oils employed for the emulsion hydrogel, in this case, sesame oil, could inhibit the oxidation processes and as a consequence decrease the generation of this group of compounds (Andargie et al., 2021; Matthäus & Özcan, 2018). Besides, these outcomes confirmed the results previously commented for TBARS (Figure 2), where T2 samples showed the lowest levels of lipid oxidation in comparison to the other two treatments. These findings stood out in comparison with recent studies, where various researchers (Pintado & Cofrades, 2020; Vargas-Ramella et al., 2020) conversely observed a significant increase of these compounds in sausages reformulated with oil emulsion gel as fat replacers. Thus, T2 could be considered a promising solution able to limit meat lipid oxidation and, as a result, the generation of aldehydes. As regards branched and cycloaldehydes, they increased ($P < 0.001$) in the reformulated sausages, though without a relevant impact on total contents. In relation to aroma notes, considering the low odor threshold of aldehydes, they could have a relevant impact on the aromatic perception of our samples (Domínguez, Purriños, et al., 2019). Indeed, they could be considered one of the main compounds derived from lipid oxidation and are able to produce a great variety of aromas (Campagnol et al., 2012). Lineal aldehydes provide floral, sweet, grassy and fruity aromas. Among them, hexanal, on the base of its high or low contents, could confer rancid or pleasant grassy aromas, respectively (Benet et al., 2015; Petričević et al., 2018). Moreover, lineal aldehydes derived from oleic acid oxidation could provide agreeable meaty notes (Domínguez, Purriños, et al., 2019). Branched compounds as butanal, 3-methyl- was associated to salty, cheesy, acorn-like, fruity aroma and its presence is normally related to the typical “ripened flavor” (Andrade et al., 2010). Besides, among cycloaldehydes, benzeneacetaldehdye contributed with acorn, rancid, and pungent odor, while benzaldehyde with floral, bitter almonds and acorn notes (Domínguez, Pateiro, et al., 2019; Domínguez, Purriños, et al., 2019). Hence, taking in consideration the percentage occupied by these compounds in relation to the total VOCs contents, it is evident that aldehydes had a significant impact on the aroma of our sausages.

The fat reformulation presented a significant (P < 0.001) influence also on total ketones (Table 5). In particular, the partial replacement of the pork fat by healthy oil emulsion hydrogels favored an increase of the total amounts of these compounds, where T1 (P < 0.001) group showed the greatest contents, followed by T2 and CON samples. Considering the ketones singularly, also butyrolactone, which occupied the greatest percentages in all treatments, recorded the major (P < 0.001) amounts in T1 and T2 samples. In addition, Domínguez, Purriños, et al. (2019) confirmed that this compound corresponded to the main lactone present in salchichón and provides to overall aroma of the final product creamy, pleasant butter, fatty, fruity and coconut-like nuances. As commented by other authors (Benet et al., 2015), lactones arise from fatty acid oxidation. Furthermore, 2,3-pentanedione and acetoin represented other two abundant compounds in this study. Previous studies stated that linear ketones derived mainly from lipid degradation (Domínguez, Purriños, et al., 2019). Actually, Stojković et al. (2015) affirmed that 2,3-pentanedione is a product of lipid degradation and is associated to the decarboxylation of β-ketoacids or to the β-oxidation of fatty acids. Considering acetoin, other studies observed that this compound represent one of the most plentiful substance in dry-fermented sausages as salchichón (Domínguez, Purriños, et al., 2019). Moreover, in this study, its values incremented significantly (P < 0.001) in both reformulated sausages, where T2 showed the greatest amounts, followed by T1 and CON samples. In this case, literature highlighted that this compound could have two potential origins, microbial carbohydrate metabolism (Petričević et al., 2018) or Maillard reactions (Domínguez, Purriños, et al., 2019). Additionally, it is characterized by a buttery, cream-like and sweet notes and has a relevant effect on the typical flavor of dry-cured meat products, owing to its really low detection odor threshold (Sidira et al., 2016). Nevertheless, it worth noting that this family of compounds did not have a relevant role in the aromatic profile of our samples, in fact, it represented only the sixth, the seventh and the eighth most abundant percentages for T1, T2 and CON samples, respectively.

Regarding the esters family, the sausages reformulated with oil emulsion hydrogels provided a significant ($P < 0.05$) decrease of the total content of these substances in comparison with the CON samples (Table 5). Considering these VOCs singularly, 11 out of the 13 esters identified also resulted to be affected ($P < 0.001$) by the type of fat source employed, although without a clear and common trend. Among them, ethyl acetate resulted to be the most plentiful ester in all treatments, in line with the results formerly obtained in the same type of product (Campagnol et al., 2012; Domínguez, Purriños, et al., 2019). In this case, the reformulated samples showed opposite tendency since T1 and T2 samples showed the lowest and the highest ($P < 0.001$) amounts in comparison with CON samples, respectively. Whereas, propanoic acid, 2-hydroxy-, ethyl ester, butanoic acid, ethyl ester and hexanoic, ethyl ester, representing other abundant compounds in our samples and recording a significant ($P < 0.001$) diminution of their amounts in the modified batches, a part from the butanoic acid, ethyl ester. However, generally speaking, most of the compounds found in our samples agree with those identified in other studies about dry-fermented sausages (Alarcón et al., 2021; Domínguez, Purriños, et al., 2019). Several studies affirmed that this class of compounds in meat products are produced from the high esterase activity of some microorganisms (as LAB or *Micrococcaceae*), promoting the enzymatic esterification of carboxylic acids and alcohols (Domínguez, Purriños, et al., 2019). In addition, some authors proposed (Domínguez, Purriños, et al., 2019) that esters with a low molecular weight can also derived from the carbohydrate metabolism. It is important to highlight that these substances are defined as very fragrant compounds (Domínguez et al., 2014), which are able to modulate and influence the global flavor of dry-ripened meat products due to their low odor threshold (Domínguez et al., 2014). In detail, fruity notes are provided by esters formed from short-chain acids while a fatty aroma is generated by those from long-chain acids (Pugliese et al., 2015). Moreover, it is recognized that ethyl esters have lower odor threshold values than methyl esters, as a consequence they have a relevant role on the product aroma, conferring the characteristic fermented sausage aroma and masking rancid notes (Andrade et al., 2010). In this study, these compounds had certainly a pivotal role for samples aroma, since 9 out of 13 esters identified, are ethyl esters. Furthermore some authors (Alarcón et al., 2021) stated that the development of the "ripened flavor" in cured meat products is related to the presence of esters and aldehydes, two of the family groups more abundant in our sausages. Indeed, total esters occupied a high percentage of the total VOCs detected in all treatments, occupying the second position of the eleven families. Hence, it is evident that this class of substances had a crucial role on the aromatic profile of our samples.

A total of two furans were detected in our dry-fermented sausages (Table 5). According to the statistical analysis, singular and total furan contents were significantly ($P < 0.001$) affected by the fat reformulation, where T1 samples showed the highest rates and T2 ones the lowest values. In particular, it was furan, 2-pentyl- to record the highest areas in all batches. While, furan, 2-ethyl- represented a minority compound. The generation of these compounds is generally associated to lipid oxidation, especially to C18:2*n*-6 and other n-6 fatty acids degradation for furan 2-pentyl-

(Akköse et al., 2017; Domínguez, Pateiro, et al., 2019), and, *n*-3 groups deterioration for furan, 2-ethyl- (Vidal et al., 2016). On the contrary, this trend was not found in our data, probably due to the oxidative stability of sesame oil, as previously discussed (Andargie et al., 2021; Matthäus & Özcan, 2018). However, furanic substances are generally responsible of a pleasant aroma, imparting green bean, butter, sweet, fruity, vegetable flavors (Domínguez, Purriños, et al., 2019) and play an important role in meat products aroma owing to their low odor threshold values. In this study, conversely, furans did not present high portions in relation to the total volatile compounds. Actually, this family showed the third (CON and T1 samples) and the lowest in contribution (T2 samples) to the volatility pattern. Hence, they cannot be considered remarkable for the aroma of our sausages.

Similarly, nitrogen compounds represented a minority family in our investigation, representing only the seventh (CON and T1 sausages) and the eighth (T2 group) most abundant group. As regards the effect of fat partial replacement, also in this case, significant differences ($P < 0.001$) were recorded among the batches, where T2 sausages showed the lowest total nitrogen compounds content, while CON and T1 samples recorded similar values. This group of compounds could play a key role in the formation of sausage aroma due to its low odor threshold values and unique olfactive notes (Corral et al., 2016). Some authors hypnotized that these compounds could take origin from the addition of potassium nitrate and sodium nitrite during the sausages manufacturing (Corral et al., 2016). On the other hand, other researchers commented that the use of nitrite is not directly correlated to aromatic compounds, but its lack could favor lipid oxidation processes, covering the odor of sulfur compounds accountable for the characteristic aroma of nitrite-ripened meat products (Thomas et al., 2014). Furthermore, some authors affirmed that the origin of these substances could derive from Strecker degradation processes from a nitrogen source, as amino acids (Corral et al., 2016).

Furthermore, also the formation of sulphur compounds is related to the amino acid breakdown (Benet et al., 2015), another important family of VOCs involved in the aroma of dry-fermented sausages. As shown in Table 5, reformulated sausages generated higher ($P < 0.001$) amounts of these compounds. In particular, dimethyl sulfone represent the most abundant sulphur compound in our samples, followed by methional and dimethyl trisulfide. These compounds, as nitrogen compounds, are considered important odorants in dry-cured meat products due to their low odor threshold values and peculiar aromatic notes (Corral et al., 2016). In particular, Strecker degradation of S-containing amino acids (as methionine and cysteine) is at the base of the generation of these aromatic compounds, defined with a pungent and potent aroma (Corral et al., 2016; Zhou et al., 2013). However, this family of substances showed a minimal contribution to the total volatile, representing the third (T2 group) and the second (CON and T1) lowest family.

Finally, a benzene-derived compound, ethylbenzene, and an ether, allyl ethyl ether, were detected and categorized as others compounds, where T1 and T2 samples showed the highest ($P < 0.001$) contents in comparison with CON group. Nevertheless, these volatile substances corresponded to a very low fraction of the total VOCs, being the group of compounds with the second (T2) and the lowest (CON and T1) involvement to the volatile profile of our sausages.

Hence, our outcomes confirmed that fat occupies a central role in the aromatic profile of meat products (Domínguez, Purriños, et al., 2019). Considering the total volatile contents, reformulated sausages reported higher ($P < 0.001$) values than CON samples, where T1 batch recorded the highest levels. In addition, total VOC and moisture resulted to be negatively correlated (r = -0.631; $P < 0.001$). Thus, according to some authors (Vargas-Ramella et al., 2020), the increment on the total VOC content in the batches T1 and T2 could be related to the low moisture percentages found in these samples (Table 2). On the contrary, lipid-derived compounds did not present exactly the same tendency. Concretely, it was T1 group to show the highest amounts of these compounds, followed by CON and T2 group. This trend could be explained by the presence of powerful antioxidant compounds in the vegetable oils employed (Vargas-Ramella et al., 2020), in particular in sesame oil. Actually, the employment of the T2 emulsion hydrogel as fat replacer demonstrated to be a promising solution, since delayed lipid oxidation processes and could enhance to the aromatic perception of dry-fermented sausages.

3.4. Sensory parameters of foal sausages

The sensorial characteristics of the foal sausages play a central role in this study since consumers' opinion and demand are strictly conditioned by these parameters. However, it is well know that animal fat replacement and the consequent alteration of the lipid profile represent demanding processes in meat products owing to the possible modification of their sensory quality (Nacak et al., 2021).

Figure 3 shows the outcomes obtained from the descriptive sensorial analysis carried out in foal sausages. Statistical analysis showed that, among the evaluated attributes, only hardness, chewiness and rancid flavor were affected ($P < 0.001$) by the fat reformulation. To this regard, sausages belonging to CON group reported the lowest ($P < 0.001$) scores for hardness and the highest ($P < 0.001$) for chewiness in line with the instrumental data obtained from the texture analysis (Table 2), as previously discussed. Concretely, reformulated samples, which showed the highest values for hardness in TPA test, obtained also the highest scores for this attribute in the sensory analysis. Moreover, T1 and T2 sausages presented the greatest values in chewiness measured instrumentally, which indicates the force (N) necessary to chew the sample. These outcomes are reflected in the panel evaluation, where tasters rated T1 and T2 samples with the lowest punctuations in comparison with CON group, confirming the difficulty to masticate them. Hence, our results are closely related to the differences observed in the texture analysis and, as above mentioned, to the lowest moisture percentages of the reformulated samples (Table 2). Similarly, other investigations on low-fat dry-fermented sausages (Fonseca et al., 2015; Lorenzo & Franco, 2012) reported that the fat reduction favored an increase of hardness scores. Also Vargas-Ramella et al. (2020) showed higher values for hardness in deer cured sausages reformulated with vegetable oil emulsions, although without significant differences. Whereas, the same authors reported that deer sausage elaborated with olive or canola oils as fat replacers were evaluated with low scores for chewiness.

Considering rancid flavor, it was T1 sausages to report the highest ($P < 0.001$) values in comparison to the other two batches. This result agrees with TBARS values, and they could be explicated by the greatest amounts of lipid-derived compounds, as aldehydes and alcohols, generated by this group of samples. As formerly discussed, these VOCs are characterized by a low odor threshold and as a results have a relevant impact on the aroma, flavor intensity and rancid flavor (Domínguez et al., 2016). In contrast, other authors (Vargas-Ramella et al., 2020) observed the greatest scores for this parameter in CON group and the lowest in the reformulated samples. These dissimilarities could be attributed to different factors, as the type of oil and the elaboration process, among others. Furthermore, odor and global flavor showed higher values in reformulated samples, although not significantly ($P > 0.05$). Moreover, according to the panelist evaluation, appearance was not altered ($P > 0.05$) by fat reformulation, although instrumental color analysis reported significant differences among samples. Thus, the panelists reported that fat reformulation did not alter ($P > 0.05$) the appearance, the taste, odor and flavor of our sausages, showing similar scores among batches, while texture and rancid flavor had to be improved.

As regards the acceptance test, all batches recorded a score higher than four, thus can be considered acceptable treatments (acceptability limit; Figure 4). In particular, T2 samples (4.89) reported significantly ($P < 0.05$) higher values than CON (4.30) and T1 (4.19) samples. Whereas, between CON and T1 batches were not significant ($P > 0.05$) differences.

Hence, it could be deduced that the reformulation of foal sausages using these emulsion hydrogels did not influence or increase the consumer acceptance of the final product. In this context, our results are in line with those obtained by Vargas-Ramella et al. (2020), who found that samples elaborated with healthy oil emulsions increased, as in the case of soy oil, or unaffected (olive and canola oils) the acceptance of deer dry-fermented sausages).

Preference test confirmed what observed in the acceptance test (Table 6). Concretely, Friedman test showed that T2 samples resulted to be the most preferred by consumers with significant differences in comparison with CON and T1 samples, which reported similar values. Finally, our results from consumers test were also reflected on the purchase intention of foal sausages (Figure 5), where the 53% of consumers indicated that they would purchase T2 sausages, the 41% of them the CON ones while only a 27% of them would buy T1 group.

Hence, our findings denoted that the use of these innovative emulsion hydrogels could improve or not change consumer acceptability in comparison with CON samples. In particular, T2 formulation demonstrated to be an appreciated and viable alternative of animal fat in the reformulation of foal fermented sausages, although texture had to be improved.

4. Conclusion

The outcomes obtained showed how the partial replacement of pork back fat by T1 and T2 emulsion hydrogels favored a significant decrease of fat content and the improvement of the nutritional profile of dry-fermented foal sausages, which obtained the claims of “source of omega-3 fatty acids” and “high omega-3 content” and showed enhanced health indices. Furthermore, T2 showed to reduce the lipid oxidation of samples, diminishing the TBARs values and the generation of most of the lipid-derived volatile compounds, while T1 reported an opposite trend. However, consumer acceptability resulted to be unaffected (T1) or improved (T2) by the lipid reformulation and, in particular, T2 samples resulted to be the most preferred. On the other hand, further studies are necessary to enhance some technological aspects of the reformulated sausages (such as texture). Besides, this study could be considered an important contribution for meat product industry, since open new possibilities towards the obtention of dry-cured meat products which can satisfy exhaustively the consumer demand, both from a nutritional as well as an environmental standpoint. Therefore, it is evident that the employ of T2 emulsion hydrogel as animal fat replacer in this product represents a viable and excellent strategy to obtain healthier and highly appreciated dry-cured foal sausages, since it demonstrated to improve the composition, nutritional quality, the oxidation stability and the sensory characteristics of the final product.

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Caption to figures

Figure 1. Appearance of foal dry-fermented sausages. CON - sausages prepared with 100% pork backfat; T1 - sausages prepared with 50% of pork backfat replaced by tigernut and algal oil mixture hydrogel; T2 - sausages prepared with 50% of pork fat replaced by sesame and algal oil mixture hydrogel.

Figure 2. TBARS values of the different formulations of foal dry-fermented sausage. $^{a-c}$ Mean values with different letter differ significantly (P < 0.05; Duncan test). Treatments: CON - sausages prepared with 100% pork backfat; T1 - sausages prepared with 50% of pork backfat replaced by tigernut and algal oil mixture hydrogel; T2 - sausages prepared with 50% of pork fat replaced by sesame and algal oil mixture hydrogel.

Figure 3. Means values for the sensory characteristics of dry-fermented foal sausages. *** (P < 0.001). Treatments: CON - sausages prepared with 100% pork backfat; T1 - sausages prepared with 50% of pork backfat replaced by tigernut and algal oil mixture hydrogel; T2 - sausages prepared with 50% of pork fat replaced by sesame and algal oil mixture hydrogel.

Figure 4. Global acceptance of dry-fermented foal sausages. $^{a-b}$ Mean values with different letter differ significantly (P < 0.05; Duncan test). Treatments: CON - sausages prepared with 100% pork backfat; T1 - sausages prepared with 50% of pork backfat replaced by tigernut and algal oil mixture hydrogel; T2 - sausages prepared with 50% of pork fat replaced by sesame and algal oil mixture hydrogel.

Figure 5. Purchase intentions of dry-fermented foal sausages. Treatments: CON - sausages prepared with 100% pork backfat; T1 - sausages prepared with 50% of pork backfat replaced by tigernut and algal oil mixture hydrogel; T2 - sausages prepared with 50% of pork fat replaced by sesame and algal oil mixture hydrogel.

Table 1. Fatty acid composition (expressed as g/100 g of fat) of fat sources

Fatty acids	Fat source				SEM	Sig.
	Pork backfat	Tigernut oil	Sesame oil	Seaweed oil		
C12:0	0.06^{b}	0.00^{a}	0.00^{a}	0.61^{c}	0.077	***
C14:0	1.01^{b}	0.08^{a}	0.00^{a}	7.74^{c}	0.973	***
C14:1*n*-5	0.01^{b}	0.00^{a}	0.00^{a}	0.11^{c}	0.014	***
C15:0	0.07^{b}	0.00^{a}	0.00^{a}	0.51^{c}	0.064	***
C16:0	19.72^{d}	12.56^{b}	8.05^{a}	15.25^{c}	1.284	***
C16:1*n*-7	1.73^{b}	0.25^{a}	0.10^{a}	5.95^{c}	0.715	***
C17:0	0.38^{c}	0.05^{a}	0.05^{a}	0.17^{b}	0.040	***
C18:0	8.87^{c}	5.05^{b}	5.02^{b}	0.49^{a}	0.896	***
9t-C18:1	0.15^{c}	0.00^{a}	0.00^{a}	0.04^{b}	0.018	***
C18:1*n*-9	31.85^{b}	59.50^{d}	35.91^{c}	0.11^{a}	6.382	***
C18:1*n*-7	2.27^{b}	0.69^{a}	0.76^{a}	5.50^{c}	0.589	***
C18:2*n*-6	13.47^{c}	8.57^{b}	37.44^{d}	0.06^{a}	4.191	***
C18:3*n*-6	0.03^{b}	0.00^{a}	0.00^{a}	0.09^{c}	0.012	***
C18:3*n*-3	0.69^{d}	0.14^{b}	0.25^{c}	0.01^{a}	0.077	***
C20:0	0.15^{b}	0.70^{d}	0.51^{c}	0.02^{a}	0.082	***
C20:1*n*-9	0.78^{d}	0.16^{c}	0.15^{b}	0.00^{a}	0.090	***
C20:2*n*-6	0.58^{c}	0.00^{a}	0.01^{b}	0.00^{a}	0.075	***
C20:3*n*-6	0.11^{c}	0.00^{a}	0.00^{a}	0.06^{b}	0.014	***
C20:4*n*-6	0.23^{c}	0.00^{a}	0.00^{a}	0.20^{b}	0.032	***
C20:3*n*-3	0.11^{b}	0.00^{a}	0.00^{a}	0.00^{a}	0.014	***
C22:0	0.00^{a}	0.13^{c}	0.10^{b}	0.00^{a}	0.017	***
C20:5*n*-3 (EPA)	0.00^{a}	0.00^{a}	0.00^{a}	1.33^{b}	0.175	***
C24:0	0.00^{a}	0.23^{c}	0.06^{b}	0.00^{a}	0.028	***
C22:5*n*-3 (DPA)	0.02^{b}	0.00^{a}	0.00^{a}	0.16^{c}	0.020	***
C22:6*n*-3 (DHA)	0.01^{a}	0.00^{a}	0.00^{a}	41.83^{b}	5.472	***
SFA	30.32^{d}	18.85^{b}	13.84^{a}	24.88^{c}	1.885	***
MUFA	36.78^{b}	60.61^{c}	36.92^{b}	11.71^{a}	5.223	***
PUFA	15.26^{b}	8.71^{a}	37.70^{c}	43.75^{d}	4.457	***
n-3	0.82^{a}	0.14^{a}	0.25^{a}	43.33^{b}	5.616	***
n-6	14.42^{c}	8.57^{b}	37.45^{d}	0.42^{a}	4.158	***
LC *n*-3	0.03^{a}	0.00^{a}	0.00^{a}	43.33^{b}	5.666	***

$^{a\text{-}d}$ Mean values in the same row (corresponding to the same parameter) with different letter differ significantly ($P < 0.05$; Duncan test); SEM: Standard error of the mean; Sig.: significance: *** ($P < 0.001$). SFA: Saturated fatty acids; MUFA: Monounsaturated fatty acids; PUFA: Polyunsaturated fatty acids; n-3: Omega-3; n-6: Omega-6; LC n-3: Long-chain omega-3

Table 2. Proximate composition, lipid oxidation, and physicochemical properties of dry-fermented foal sausages

Parameters	Treatments			SEM	Sig.
	CON	T1	T2		
Chemical composition					
Moisture (g/100 g)	33.57^{b}	28.57^{a}	28.63^{a}	0.396	***
Fat (dry matter) (g/100 g)	36.91^{b}	30.23^{a}	30.59^{a}	0.455	***
Protein (dry matter) (g/100 g)	44.76	46.02	44.63	0.287	ns
Ash (dry matter) (g/100 g)	5.17^{a}	6.92^{b}	6.60^{b}	0.187	***
Color parameters					
L*	38.39^{b}	32.59^{a}	32.42^{a}	0.413	***
a*	9.73^{b}	8.03^{a}	11.00^{b}	0.296	***
b*	9.14^{b}	7.36^{a}	7.84^{a}	0.227	**
pH	5.05	5.11	5.11	0.026	ns
Texture parameters					
Hardness (N)	152.39^{a}	317.29^{c}	283.16^{b}	10.598	***
Springiness (mm)	0.57^{b}	0.55^{ab}	0.53^{a}	0.005	*
Cohesiveness	0.37	0.36	0.36	0.004	ns
Gumminess (N)	57.20^{a}	110.50^{b}	103.96^{b}	4.123	***
Chewiness (N·mm)	30.70^{a}	56.24^{b}	49.65^{b}	1.931	***

$^{a-c}$ Mean values in the same row (corresponding to the same parameter) with different letter differ significantly ($P < 0.05$; Duncan test); SEM: Standard error of the mean; Sig.: significance: *** ($P < 0.001$); ** ($P < 0.01$); * ($P < 0.05$); ns (not significant). Treatments: CON - sausages prepared with 100% pork backfat; T1 - sausages prepared with 50% of pork backfat replaced by tigernut and algal oil mixture hydrogel; T2 - sausages prepared with 50% of pork fat replaced by sesame and algal oil mixture hydrogel

Table 3. Fatty acid composition (expressed as g/100 g of fat) of dry-fermented foal sausages

Fatty acids	Treatments			SEM	Sig.
	CON	T1	T2		
C12:0	0.09[b]	0.08[a]	0.09[b]	0.001	***
C14:0	1.70[b]	1.58[a]	1.67[b]	0.017	*
C14:1*n*-5	0.08[a]	0.08[a]	0.10[b]	0.003	*
C15:0	0.12[b]	0.10[a]	0.11[a]	0.001	***
C16:0	23.19[b]	20.86[a]	20.46[a]	0.187	***
C16:1*n*-7	2.86[b]	2.59[a]	2.74[ab]	0.043	*
C17:0	0.39[c]	0.28[a]	0.29[b]	0.006	***
C18:0	8.42[b]	7.00[a]	7.04[a]	0.089	***
9t-C18:1	0.16[b]	0.11[a]	0.11[a]	0.003	***
C18:1*n*-9	33.27[a]	36.76[b]	32.89[a]	0.275	***
C18:1*n*-7	2.16[b]	1.72[a]	1.77[a]	0.026	***
C18:2*n*-6	13.04[b]	11.60[a]	17.26[c]	0.298	***
C18:3*n*-3	2.46[a]	2.60[b]	2.99[c]	0.038	***
C20:0	0.14[a]	0.24[c]	0.20[b]	0.005	***
C20:1*n*-9	0.67[b]	0.49[a]	0.49[a]	0.010	***
C20:2*n*-6	0.48[b]	0.33[a]	0.33[a]	0.009	***
C20:3*n*-6	0.12[b]	0.10[a]	0.09[a]	0.002	***
C20:4*n*-6	0.30[b]	0.25[a]	0.26[a]	0.004	***
C20:3*n*-3	0.14[c]	0.12[a]	0.13[b]	0.002	***
C20:5*n*-3 (EPA)	0.03[a]	0.05[b]	0.05[b]	0.001	***
C22:5*n*-3 (DPA)	0.10[a]	0.10[a]	0.11[a]	0.003	ns
C22:6*n*-3 (DHA)	0.02[a]	0.49[b]	0.57[c]	0.030	***
SFA	34.16[b]	30.31[a]	30.00[a]	0.277	***
MUFA	39.29[a]	41.85[b]	38.21[a]	0.288	***
PUFA	16.75[b]	15.67[a]	21.83[c]	0.340	***
n-3	2.75[a]	3.36[b]	3.85[c]	0.063	***
n-6	13.98[b]	12.30[a]	17.97[c]	0.297	***
LC *n*-3	0.15[a]	0.64[b]	0.72[c]	0.031	***
n-6/*n*-3	5.12[c]	3.68[a]	4.68[b]	0.080	***
PUFA/SFA	0.49[a]	0.52[b]	0.73[c]	0.013	***
TI	0.95[c]	0.79[b]	0.73[a]	0.011	***
AI	0.54[c]	0.47[b]	0.45[a]	0.005	***
h/H	2.06[a]	2.36[b]	2.50[c]	0.023	***

[a-c] Mean values in the same row (corresponding to the same parameter) with different letter differ significantly ($P < 0.05$; Duncan test); SEM: Standard error of the mean; Sig.: significance: *** ($P < 0.001$). Treatments: CON - sausages prepared with 100% pork backfat; T1 - sausages prepared with 50% of pork backfat replaced by tigernut and algal oil mixture hydrogel; T2 - sausages prepared with 50% of pork fat replaced by sesame and algal oil mixture hydrogel. SFA: Saturated fatty acids; MUFA: Monounsaturated fatty acids; PUFA: Polyunsaturated fatty acids; *n*-3: Omega-3; *n*-6: Omega-6; LC *n*-3: Long-chain omega-3; TI: Thrombogenic index; AI: Atherogenic index; h/H: Hypo/hypercholesterolemic fatty acids ratio

Table 4. Effect of fat source on hydrocarbons, terpenes and terpenoids, acids, and alcohols (expressed as AU × 104/g) of dry-fermented foal sausages

Volatile compounds	LRI	*m/z*	Treatments			SEM	Sig.
			CON	T1	T2		
Pentane	500	43	78.86[b]	4.62[a]	75.45[b]	4.585	***
Heptane	700	71	1.25[b]	2.04[c]	0.86[a]	0.076	***
Octane	800	85	7.07[a]	15.19[b]	8.60[a]	0.534	***
Isopropylcyclobutane	819	55	0.32[a]	0.56[b]	2.12[c]	0.099	***
3,5-Octadiene, (Z,Z)-	831	81	0.14[a]	0.42[c]	0.25[b]	0.016	***
Decane	1000	57	8.00[b]	10.00[c]	0.92[a]	0.485	***
Heptane, 2,2,4,6,6-pentamethyl-	1001	56	4.45[a]	5.42[b]	4.60[a]	0.113	***
Total lineal hydrocarbons			95.32[b]	32.27[a]	86.08[b]	3.928	***
Total branched hydrocarbons			4.45[a]	5.42[b]	4.60[a]	0.113	***
Total cyclic hydrocarbons			0.32[a]	0.56[b]	2.12[c]	0.099	***
Total hydrocarbons			100.1[b]	38.25[a]	92.80[b]	3.905	***
m-Xylene	907	91	0.81[a]	1.54[c]	1.07[b]	0.043	***
α-Phellandrene	949	93	138.6[a]	167.5[b]	195.4[b]	6.365	***
Cyclofenchene	956	93	63.91[a]	137.0[b]	144.5[b]	5.791	***
Camphene	973	121	0.87[a]	1.81[b]	1.79[b]	0.067	***
Sabinene	996	93	143.2[a]	235.0[b]	252.3[b]	8.795	***
(-)-β-Pinene	998	93	109.2[a]	141.4[b]	153.0[b]	5.078	***
β-Myrcene	1006	93	43.13[a]	104.4[b]	109.1[b]	4.267	***
3-Carene	1023	93	170.9[a]	345.2[b]	330.5[b]	10.990	***
α-Terpinene	1031	121	14.44[a]	31.35[b]	61.34[c]	2.557	***
D-Limonene	1040	93	176.3[a]	335.5[b]	324.7[b]	10.896	***
o-Cymene	1044	119	296.2[a]	427.6[c]	334.4[b]	8.873	***
Eucalyptol	1049	154	2.06[a]	2.76[b]	2.74[b]	0.061	***
β-Ocimene	1054	93	0.84[a]	2.64[b]	3.46[c]	0.147	***
γ-Terpinene	1063	93	45.44[a]	74.26[b]	96.15[c]	3.777	***
(+)-4-Carene	1086	121	7.68[a]	20.69[b]	28.45[c]	1.244	***
Styrene, 3,4-dimethyl-	1099	117	5.11	5.89	6.05	0.201	ns
Linalool	1115	71	5.33[a]	8.91[c]	7.77[b]	0.266	***
(+)-trans-4-Thujanol	1124	111	2.92[a]	4.42[b]	3.99[b]	0.155	***
(-)-Terpinen-4-ol	1173	111	27.96[a]	33.21[b]	33.12[b]	0.973	*
α-Terpineol	1187	59	2.48[a]	3.17[b]	3.04[b]	0.081	***
Safrole	1246	162	88.45[a]	120.9[b]	120.5[b]	2.499	***
δ-Elemene	1260	136	3.12[a]	5.54[b]	5.80[b]	0.221	***
α-Copaene	1286	161	23.91[a]	32.02[b]	31.02[b]	0.633	***
Helminthogermacrene	1297	147	0.59[a]	0.81[b]	0.81[b]	0.019	***
Caryophyllene	1321	133	56.04[a]	73.69[b]	79.41[b]	2.375	***
1,5,9,9-Tetramethyl-1,4,7-cycloundecatriene	1339	93	6.29[a]	7.91[b]	8.18[b]	0.208	***

Myristicin	1371	192	6.98^{a}	9.65^{b}	9.54^{b}	0.221	***
Total terpenes and terpenoids			1443^{a}	2335^{b}	2348^{b}	60.681	***
Butanoic acid	898	60	52.33^{a}	65.21^{b}	56.88^{a}	1.573	**
Hexanoic acid	1055	60	10.57^{b}	16.35^{c}	5.60^{a}	0.603	***
Total acids			62.91^{a}	81.57^{b}	62.48^{a}	1.807	***
Glycidol	501	44	16.55^{a}	25.70^{b}	24.64^{b}	0.729	***
2-Propanol	532	45	7.39^{b}	4.53^{a}	4.63^{a}	0.220	***
1-Propanol	571	59	0.41^{b}	0.52^{c}	0.20^{a}	0.021	***
1-Propanol, 2-methyl-	648	43	0.09^{a}	0.15^{b}	0.30^{c}	0.012	***
1-Butanol	704	56	0.93^{c}	0.78^{b}	0.41^{a}	0.038	***
1-Penten-3-ol	725	57	40.64^{b}	42.81^{b}	6.49^{a}	2.314	***
1-Butanol, 3-methyl-	798	70	1.38^{a}	1.39^{a}	4.24^{b}	0.182	***
1-Butanol, 2-methyl-	801	56	0.41^{a}	0.45^{a}	1.14^{b}	0.047	***
1-Pentanol	834	70	16.68^{c}	11.73^{b}	1.70^{a}	0.866	***
[R,R]-2,3-butanediol	902	45	51.47^{a}	145.0^{c}	110.6^{b}	6.513	***
1-Hexanol	935	56	8.11^{b}	13.68^{c}	3.14^{a}	0.668	***
Benzyl alcohol	1096	108	55.28^{a}	81.78^{b}	64.96^{a}	3.518	**
1-Octanol	1096	69	5.21^{a}	6.58^{b}	4.91^{a}	0.159	***
Phenylethyl Alcohol	1150	91	1.84^{b}	0.66^{a}	4.36^{c}	0.213	***
Total alcohols			206.4^{a}	335.8^{c}	231.7^{b}	8.248	***

$^{a-c}$ Mean values in the same row (corresponding to the same parameter) with different letter differ significantly ($P < 0.05$; Duncan test); SEM: Standard error of the mean; Sig.: significance: *** ($P < 0.001$); ** ($P < 0.01$); * ($P < 0.05$); ns (not significant). Treatments: CON - sausages prepared with 100% pork backfat; T1 - sausages prepared with 50% of pork backfat replaced by tigernut and algal oil mixture hydrogel; T2 - sausages prepared with 50% of pork fat replaced by sesame and algal oil mixture hydrogel. LRI: lineal retention index calculated for DB-624 capillary column (30 m × 0.25 mm id, 1.4 µm film thickness; J&W Scientific, Folsom, CA, USA), installed on a gas chromatograph equipped with a mass selective detector; *m/z*: quantification ion.

Table 5. Effect of fat source on aldehydes, ketones, esters, furans, nitrogen compounds, sulphur compounds, and other volatile compounds (expressed as AU × 10^4/g) of dry-fermented foal sausages

Volatile compounds	LRI	*m/z*	Treatments			SEM	Sig.
			CON	**T1**	**T2**		
2-Propenal	524	56	0.17^{ab}	0.20^{b}	0.15^{a}	0.007	*
Propanal	526	58	21.67^{b}	40.97^{c}	0.83^{a}	2.026	***
Butanal	584	72	0.45^{b}	0.48^{b}	0.08^{a}	0.026	***
Butanal, 3-methyl-	659	58	3.31^{a}	11.18^{b}	10.08^{b}	0.476	***
Butanal, 2-methyl-	671	58	1.44^{a}	4.44^{b}	4.27^{b}	0.201	***
Pentanal	724	57	43.71^{b}	47.07^{b}	6.13^{a}	2.547	***
2-Butenal, 2-methyl-	792	84	0.40^{a}	4.33^{c}	0.96^{b}	0.226	***
Hexanal	852	56	195.1^{b}	244.3^{c}	29.49^{a}	11.883	***
Heptanal	953	70	18.90^{c}	15.99^{b}	3.37^{a}	0.851	***
2-Heptenal, (Z)-	1013	83	10.90^{c}	4.36^{b}	0.51^{a}	0.571	***
Benzaldehyde	1020	106	15.16^{a}	26.96^{c}	21.16^{b}	0.843	***
2,4-Heptadienal, (E,E)-	1063	81	10.07^{b}	10.99^{b}	1.86^{a}	0.529	***
Benzeneacetaldehyde	1091	91	21.03^{a}	24.66^{a}	105.5^{b}	4.971	***
Nonanal	1117	98	4.28^{b}	5.90^{c}	1.95^{a}	0.223	***
Total aldehydes			346.6^{b}	441.9^{c}	186.3^{a}	13.671	***
2-Butanone	594	72	1.11^{a}	4.54^{c}	3.96^{b}	0.202	***
2,3-Pentanedione	731	100	7.66^{b}	19.33^{c}	1.45^{a}	0.961	***
Acetoin	780	45	5.39^{a}	8.17^{b}	10.64^{c}	0.381	***
2-Heptanone	947	58	2.68^{b}	2.50^{b}	0.63^{a}	0.131	***
Butyrolactone	1022	86	23.59^{a}	37.87^{b}	36.81^{b}	1.167	***
γ-Pentalactone	1052	56	5.83^{b}	4.47^{a}	5.10^{ab}	0.211	*
γ-Caprolactone	1128	85	2.10^{c}	1.72^{b}	0.69^{a}	0.091	***
Total Ketones			48.36^{a}	78.60^{c}	59.27^{b}	1.924	***
Acetic acid, methyl ester	538	74	0.35^{a}	0.57^{b}	0.36^{a}	0.022	***
Ethyl Acetate	598	43	342.2^{b}	307.4^{a}	381.5^{c}	6.654	***
Formic acid, 2-propenyl ester	671	57	3.63^{a}	7.16^{b}	6.69^{b}	0.255	***
Propanoic acid, ethyl ester	731	57	22.85^{b}	52.04^{c}	8.35^{a}	2.612	***
Butanoic acid, ethyl ester	841	71	81.34	74.62	72.34	2.974	ns
Propanoic acid, 2-hydroxy-, ethyl ester	878	45	148.8^{b}	124.2^{a}	126.3^{a}	2.675	***
Butanoic acid, 2-methyl-, ethyl ester	891	102	4.47^{a}	4.05^{a}	5.76^{b}	0.136	***
Butanoic acid, 3-methyl-, ethyl ester	895	88	9.69^{b}	7.80^{a}	12.53^{c}	0.317	***
Pentanoic acid, ethyl ester	940	85	9.41	8.95	8.40	0.205	ns
Hexanoic acid, ethyl ester	1024	99	55.43^{c}	39.71^{b}	21.61^{a}	2.054	***
Acetic acid, hexyl ester	1037	56	2.72^{b}	3.57^{c}	1.70^{a}	0.110	***
Octanoic acid, ethyl ester	1169	88	18.39^{b}	11.65^{a}	10.08^{a}	0.568	***
Decanoic acid, ethyl ester	1293	88	15.81^{b}	5.76^{a}	6.48^{a}	0.586	***
Total esters			715.1^{b}	647.5^{a}	662.1^{a}	10.972	*

Furan, 2-ethyl-	699	96	4.14^{b}	4.22^{b}	0.67^{a}	0.240	***
Furan, 2-pentyl-	1012	81	9.75^{b}	16.08^{c}	3.80^{a}	0.738	***
Total furans			13.89^{b}	20.30^{c}	4.46^{a}	0.922	***
2-Propanamine	724	58	11.71^{b}	13.86^{c}	4.56^{a}	0.536	***
Methylformamide	880	59	3.04^{b}	3.73^{c}	0.21^{a}	0.208	***
Propane, 2-nitro-	900	46	1.54^{a}	3.30^{b}	3.00^{b}	0.140	***
4-Imidazolemethanol	945	98	1.49^{a}	2.01^{b}	2.14^{b}	0.065	***
Pyrolo[3,2-d]pyrimidin-2,4(1H,3H)-dione	1015	151	40.13^{b}	37.85^{b}	34.31^{a}	0.759	**
Total nitrogen compounds			57.91^{b}	60.75^{b}	44.22^{a}	1.224	***
Methional	978	104	1.16^{a}	2.84^{b}	4.61^{c}	0.190	***
Dimethyl trisulfide	1011	126	1.37	1.09	1.10	0.058	ns
Dimethyl sulfone	1049	79	4.58^{a}	6.75^{b}	14.27^{c}	0.550	***
Total sulphur compounds			7.11^{a}	10.68^{b}	19.97^{c}	0.687	***
Allyl ethyl ether	671	58	1.57^{a}	4.55^{b}	4.32^{b}	0.201	***
Ethylbenzene	899	91	0.38^{a}	1.02^{c}	0.47^{b}	0.037	***
Total others			1.95^{a}	5.57^{c}	4.78^{b}	0.220	***
Total volatile compounds			3003^{a}	4056^{c}	3716^{b}	61.657	***

$^{a-c}$ Mean values in the same row (corresponding to the same parameter) with different letter differ significantly (*P* < 0.05; Duncan test); SEM: Standard error of the mean; Sig.: significance: *** (*P* < 0.001); ** (*P* < 0.01); * (*P* < 0.05); ns (not significant). Treatments: CON - sausages prepared with 100% pork backfat; T1 - sausages prepared with 50% of pork backfat replaced by tigernut and algal oil mixture hydrogel; T2 - sausages prepared with 50% of pork fat replaced by sesame and algal oil mixture hydrogel. LRI: lineal retention index calculated for DB-624 capillary column (30 m × 0.25 mm id, 1.4 µm film thickness; J&W Scientific, Folsom, CA, USA), installed on a gas chromatograph equipped with a mass selective detector; *m/z*: quantification ion

Table 6. Global preference values of dry-fermented foal sausages

Sample most favorite		**Sample least favorite**
T2 (121)		
	CON (93)	T1 (92)
	F_{test}=10.63 > F(α=0.05)=5,99	

Samples in the same row not have significant differences ($P > 0.05$); samples in different rows have significant differences ($P < 0.05$). The numbers in brackets are Σ score. Treatments: CON - sausages prepared with 100% pork backfat; T1 - sausages prepared with 50% of pork backfat replaced by tigernut and algal oil mixture hydrogel; T2 - sausages prepared with 50% of pork fat replaced by sesame and algal oil mixture hydrogel