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Paolo De Caria, Paolo Fortugno, Matteo Bognanno, Francesco Foti, Pasquale Caparra, Caterina Cilione, Salvatore Bognanno, Martino Musati, Guido Mangione, Manuel Scerra, 2026.

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Small Ruminant Research, volume 263, article 107851. ISSN: 0921-4488

which has been published in final doi: https://doi.org/10.1016/j.smallrumres.2026.107851

Enhancement of lamb meat quality: Effects of dietary supplementation of pistachio hulls

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Abstract

Pistachio hulls were evaluated as a nutrient source in the Sarda lamb finishing system in this study. Twenty male lambs (initial body weight 32.2 ± SD 0.42 kg) were fed for 40 days with either a concentrate diet (169 g/kg dry matter of crude protein, control group) or the same concentrate diet of the control group in which 20% (on a dry matter basis) of the cereals were replaced with pistachio hulls (HP20 group). Hay (Sulla, *Hedysarum coronarium*) was given ad libitum in a separate feeder. The results showed that no alterations in growth performance of lambs occurred following feeding with pistachio hulls; however, the feed conversion ratio (FCR) of lambs was slightly higher in the PH20 group than in the other dietary treatments (P = 0.049). Intramuscular fat content in lambs fed the PH20 diet was greater (P = 0.032) than in the control lambs. Lambs fed the PH20 diet had greater amounts of stearic acid (P = 0.036), rumenic acid (P = 0.005), and α-linolenic acid (C18:3 n-3; P = 0.049) in their *longissimus thoracis et lumborum* muscle (LTL). During 7 days of aerobic storage at 4 °C, thiobarbituric acid reactive substances (TBARS) increased in both groups ($P < 0.001$); however, concentrations of TBARS were significantly lower ($P < 0.001$) in PH20 meat compared to control meat. Lastly, the croma (C*) of lambs fed the PH20 diet were significantly greater than those fed the control diet (P = 0.014), indicating improved colour stability of PH20 meat compared to control meat.

Overall, replacing 20% of dietary dry matter with pistachio hulls preserved animal performance while improving selected nutritional and oxidative stability traits of lamb meat.

Keywords: by-products, fatty acid, lipids, oxidation, sustainability.

Introduction

Interest in utilizing agro-industrial by-products as an alternative feed resource for livestock production has grown due to these products' potential to enhance both economic sustainability of animal production and to diminish the environmental negative consequences of products obtained from animal sources. Ruminators are especially suited to utilize fibrous plant material and residues produced from processing those plants inedible by humans and transform this residue into valuable products for animals (Godfray et al., 2010; Simitzis and Deligeorgis, 2018). In addition, many by-products have high concentrations of bioactive compounds, with polyphenols being the major class of these compounds, that will potentially provide positive attributes to livestock health due to their antioxidant, antimicrobial and anti-inflammatory properties; and can also increase the oxidative stability of meat and milk products (López-Andrés et al., 2014; Routray and Orsat, 2017; Alasalvar et al., 2020; Bešlo et al., 2022).

The processing of crops from the Mediterranean region such as fruits, olive, citrus and tree nuts produces large quantities of lignocellulosic residues containing high levels of fibre and polyphenols. Polyphenols included in ruminator diets at moderate levels can also influence rumen microbial activity and improve nitrogen use, as several studies have reported (Min et al., 2003; Waghorn et al., 1987; Makkar et al., 2007). Numerous studies have indicated that by-products with high concentrations of polyphenols can enhance the oxidative stability of meat products and modulate the biohydrogenation of polyunsaturated fatty acids in the rumen, without negatively affecting animal performance (Scerra et al., 2018; Elhadef et al., 2021; Scerra et al., 2021; Menci et al., 2023; Musati et al., 2024b; Scerra et al., 2024; Zhao et al., 2023).

Pistachio hulls (which is the outer pericarp of the pistachio nut) are an abundant but underutilized by-product of the pistachio nut manufacturer; In Italy, pistachio cultivation is concentrated predominantly in Sicily, which accounts for more than 90% of the national production (FAOSTAT, 2022; Barone and Marra, 2004). Pistachio by-products are abundant in polyphenols, tannins and flavonoids, and have been reported to have positive health benefits to animals, improve product quality, and reduce the greenhouse gas methane (Gentile et al., 2007; Abid et al., 2019; Hassan et al., 2020; Noruzi et al., 2024). Research with lambs has demonstrated that feeding pistachio by-products (pistachio green hull aqueous extract or a mixture of soft hulls, leaves, and twigs) at levels of up to 30% in the diet does not negatively affect growth performance, and may even increase the antioxidant status of the meat and reduce the amount of lipid oxidation (Norouzian and Ghiasi, 2012; Kazemi et al., 2024; Noruzi et al., 2024). To date however, there is very limited information regarding the effect of pistachio hulls on growth performance and carcass characteristics, as well as the fatty acid profile of the meat and meat oxidative stability of growing lambs. Therefore, the objective of the current research was to evaluate the effects of adding 20% pistachio hulls to the diet of Sarda male lambs on growth performance, meat composition and oxidative stability of the meat.

2. Materials and Methods

2.1 Animal Management and Experimental Design

The experimental methods of this trial have been authorized by the Animal Welfare Committee of the University of Reggio Calabria (protocol No. 0000723).

The trial involved twenty Sarda male lambs. Lambs were weaned at 60 days of age and fed for 80 days with a commercial concentrate including, on a dry matter basis, 60% cereal mix, made up of equal quantities of maize and barley, 20% fava bean, 17% wheat bran, 3% vitamin mineral premix and with Sulla hay (*Hedysarum coronarium*) in a separate feeder (*ad libitum*). Subsequently, at the average initial body weight 32.2 ± SD 0.42 kg, the lambs were allocated in individual straw-bedded pens and randomly assigned to two dietary treatments (n=10), balanced for the initial body weight, and adapted to the respective experimental diets for 6 days. At the end of the adaptation period, each group was fed *ad libitum* with one of the following concentrate-based diet for 40 days: the same commercial maize-barley-faba bean based concentrate used after weaning (control); control diet with 20 % of pistachio hulls inclusion (on a dry matter basis) as partial replacement of barley, maize and faba bean (PH20). Diets were formulated to provide comparable levels of crude protein and metabolizable energy. The pistachio by-product was supplied by the organic farm Di GaLa (San Biagio Platani, AG). The by-product provided was free of twigs or leaves and therefore consisted exclusively of pistachio hulls. Ingredients and the chemical composition of the experimental diets are reported In Table 1. The ingredients of each concentrate mixture were ground to avoid the selection of ingredients and pelleted. Sulla hay was given *ad libitum* in a separate feeder.

The experimental diets were provided twice daily, early morning and late afternoon; refused feeds were collected from the individual pens and weighed to estimate the amount of feed intake. Daily voluntary feed intake was measured by recording the amounts of feed offered and refused.

Once a week the animals were weighed to assess average daily gain. At the end of the trial, all the lambs were slaughtered on the same day in a commercial abattoir according to the European Union welfare guidelines (Directive 2010/63/EU; CR 1099/2009). The experimental diet and water were available to lambs until approximately 4 h before slaughter. Lambs were firstly stunned by a captive bolt and exsanguinated. Each carcass was immediately weighted and stored at 4 °C for 24 h. Subsequently, the entire *longissimus thoracis et lumborum* muscle (LTL) was excised from both sides. The right LTL was vacuum- sealed and stored at - 30 °C for later analysis of FA composition, proximate composition and α-tocopherol. The left LTL was designated for shelf-life study and subsequent evaluations of lipid oxidation.

2.2 Analyses on feed and meat

Throughout the feeding trial, feed samples were collected weekly from each experimental diet and stored under vacuum at −30 °C. At the end of the trial, the samples were ground and pooled to obtain representative composite samples of each dietary treatment. The proximate composition of the representative samples of the experimental diets was evaluated through analysis of crude protein, ether extract, and ash using the analysis methods developed by the Association of Official Analytical Chemists (AOAC, 1995), which are identified by the references 984.13, 920.39, and 942.05 respectively. The fiber fraction was assessed for neutral detergent fiber (NDF) by using the analysis method described by Van Soest et al. (1991). Metabolizable energy was estimated based on Cannas et al. (2004). The total lipids used for fatty acid profiling were extracted and quantified using the methods set forth by Gray et al. (1967).

Vitamin E was extracted from feedstuffs and quantified following the method of Rufino-Moya et al. (2020). Briefly, 200 mg of diet or by-product were extracted with a 1:1:1 mixture of methanol, acetone, and petroleum ether. After centrifugation (1000 × g for 5 min), the supernatant was collected three times. The combined extracts were evaporated under a nitrogen stream at 40 °C, and the residue was reconstituted in methanol and filtered through 0.22 µm PTFE filters prior to analysis. While, the content of α-tocopherol in LTL was determined according to the method described by Bertolín et al. (2018), with the modifications reported by Menci et al. (2022). Briefly, a 2.5 g sample was mixed with 0.2 g of ascorbic acid and 7.5 mL of 10% KOH in ethanol:water and incubated overnight on an orbital shaker. Lipids were then extracted twice with 5 mL of hexane:ethyl acetate (9:1, containing 25 mg/L BHT), followed by centrifugation. The combined supernatants were evaporated under a nitrogen stream, and the residues were reconstituted in methanol and filtered prior to analysis. Vitamin was separated and quantified by UHPLC (Nexera, Shimadzu, Japan) using a C18 column (Zorbax ODS; 25 cm × 4.6 mm, 5 µm). Instrumental conditions followed Natalello et al. (2022). Quantification was performed using external calibration curves prepared with pure standards (Merck Life Science s.r.l., Milan, Italy).

To determine the total amount of total polyphenols present in a feed sample, an aqueous/acetic acid (acetone) solvent system was employed. Quantification of total polyphenols was carried out using the Folin-Ciocalteu colorimetric method (Makkar et al., 1993).

Meat sample analyses were performed on *LTL* muscle. Moisture, crude fat, ash and crude protein levels were evaluated according to standard AOAC analyses (AOAC, 1995; methods 950.46, 991.36, 920.153, and 984.13). The meat colour properties measured included L* (lightness), a* (red), b* (yellow), chroma (C*), and hue angle(H*) based on the CIELAB system and were determined by conducting three separate measurements with a Minolta CR-300 colorimeter (CR-300 Model, Minolta Co., Ltd., Osaka, Japan) and by using the D65 light source for the measurement after calibration with a standard white tile.

2.3 Oxidative stability of lipids and fatty acid composition in meat samples

The *LTL* sections were kept in a refrigerator at 4 °C under an environment that is uninterrupted by oxygen through cover sheets and underwent analysis on the fresh item after different storage times; T0 (0 days), T4 (4 days) and T7 (7 days).

The thiobarbituric acid reactive substances (TBARS) assay is an indicator of lipid oxidation and was measured using the Siu and Draper procedure (978). For this analysis, 2.5 g of meat was homogenized (with Ultraturrax, model T25, IKA-Werke GmbH & Co.KG, Staufen, Germany) in 12.5 mL of distilled water. The resulting homogenate was then treated with 12.5 mL of 5% (w/v) trichloroacetic acid, thoroughly vortexed, and subsequently filtered through Whatman No. 1 filter paper. Four mL of a tested homogenate was aliquotted and mixed with 1 mL thiobarbituric Acid (0.02 M) and incubated at 80 °C for 90 minutes. The absorbance was read at 532 nm using a double beam UV Spectrophotometer (Shimadzu Corp., Milan, Italy, UV-1800). The data was expressed in mg of malondialdehyde (MDA)/kg of meat.

Using the method proposed by Folch, Lees and Sloane Stanley (1957), intramuscular fat was obtained from 5 g of fresh meat by using chloroform/methanol (2:1, v/v). Then, the lipid extract was methylated with 1 ml of hexane and 0.05 ml of 2 N methanolic KOH (IUPAC, 1987), and C19:0 was used as the internal standard.

Fatty acid methyl esters were analyzed with the use of a Varian CP-3900 gas chromatogram (Mitchell Drive Walnut Creek CA USA). This chromatogram has a CP-Sil 88 column (100M × 0.25 mm i.d., film thickness 0.25µm; Agilent J&W) and one microliter of sample was injected using helium as the carrier gas at a flow rate of 0.7 mL/min. The chromatograph conditions are as follows: the flame ionization detector (FID) temperature is set at 260 °C; the injection port (split/splitless mode) is at 220 °C with an injection flow of 120 mL/min; column oven temperature begins with 4 minutes at 140 °C before increasing to a final temperature of 220 °C at 4 °C/min. The identification of individual fatty acids is done by comparing the retention time of the fatty acid methyl esters (FAME) with that of the standard FAME mixture (Supelco Inc., Bellefonte PA USA) and are quantified in terms of mg/100 g of total fatty acids.

2.4 Statistical analysis

A one-way ANOVA was used to statistically analyze the effects of dietary treatments on animal performance, feed intake, chemical composition of muscle, and intramuscular fatty acid composition, considering the individual lambs as the experimental units. The assumption of normality of the data distribution was assessed using the Shapiro–Wilk test. All statistical analyses were performed using Minitab software (version 14, Minitab Inc., State College, PA). For testing the effect of the dietary treatment, time of storage, and their interaction as fixed factors on colour and lipid oxidation parameters was applied a mixed model for repeated measures, with individual lambs as random factor. The Tukey test for multiple comparisons was performed when $P \leq 0.05$, whereas tendencies toward significance were considered when $0.05 < P \leq 0.10$.

Results

Table 2 summarizes how dietary treatments impacted *in vivo* performance, and chemical composition of the *LTL* muscle of Sarda lambs. The inclusion of 20% pistachio hulls had little effect on the final body weight, carcass weight, dry matter intake and average daily gain of lambs ($P > 0.05$). The final body weight of the control and PH20 lambs was not significantly different, and no differences in carcass yields or total feed intake were observed between lambs fed the two diets. The average daily gain of lambs on the PH20 group was numerically lower than that of the control group, but this difference was not statistically significant ($P > 0.05$). Conversely, the feed conversion ratio (FCR) was significantly affected by dietary treatment ($P < 0.05$), with lambs fed the PH20 diet showing higher FCR values, indicating lower feed efficiency compared with control lambs.

Regarding the chemical composition, the levels of alpha-tocopherol and ether extract were significantly higher ($P < 0.001$) in the PH20 group compared with the control group (Table 2).

The inclusion of pistachio hulls in the diet markedly influenced the fatty acid profile of muscle tissue (Table 3). In lambs, the experimental diet (20% pistachio hulls) resulted in a significant accumulation of several fatty acids in muscle compared with the control group. Furthermore, the intramuscular fat (IMF) level was also higher ($P < 0.05$) in meat from PH20 group than in control group. Fatty acids that increased significantly included stearic acid (C18:0, $P < 0.05$), *trans-9*-octadecenoic acid (C18:1 *trans-9*, $P < 0.01$), rumenic acid (C18:2 *cis–9, trans-11*, $P < 0.01$) and α-linolenic acid (C18:3 n-3, $P < 0.05$); furthermore vaccenic acid (C18:1 *trans–11*) was tendentially higher ($P = 0.057$; trend toward significance) in meat from PH20 group compared with the control group. However, no significant differences were observed in oleic acid (C18:1 *cis-9*), total saturated fatty acids (SFA), total monounsaturated fatty acids (MUFA), or total polyunsaturated fatty acids (PUFA) levels ($P > 0.05$). Total n-6 and n-3 fatty acid composition, as well as the n-6/n-3 ratio, were not affected by dietary treatment.

The pattern of lipid oxidation over time and diet was evaluated in Figure 1, through changes in TBARS value during refrigerated storage. The dietary treatment affected secondary products of lipid oxidation, with an average higher ($P < 0.05$) TBARS value in control meat than in PH20 meat. A similar trend was shown by interaction diet × time in TBARS, with notable differences only starting from day 4 of storage ($P < 0.01$). In particular, at day 0 the mean MDA values did not differ between the control and PH20 groups ($P > 0.05$). However, after four days of storage, MDA levels increaded in both groups. By day 7, the control group exhibited significantly higher MDA values than the PH20 group ($P < 0.001$), indicating greater lipid oxidation.

Dietary treatment and storage time influenced meat colour parameters. Muscles from lambs fed the pistachio hulls diet (PH20) showed tendentially higher a* (redness) values ($P = 0.052$) than those from the control group. However, redness (a*) values decreased over storage time ($P < 0.001$) in both groups, with a less pronounced decline in the PH20 group compared with control group (diet × time interaction, $P < 0.025$). b* (yellowness) values were not affected by dietary treatment ($P > 0.05$), but decreased during storage ($P < 0.001$). Lightness (L*) was also unaffected by diet but decreased progressively during refrigeration ($P < 0.001$). Chroma (C*) values were higher in the PH20 group at all time points ($P < 0.05$), although no diet × time interaction was observed ($P > 0.05$). No significant effect of diet was found on *hue* angle (H)* values; however, H* decreased over the storage period ($P < 0.001$).

Discussion

The present study evaluated the effects of partially replacing conventional cereals with pistachio hulls at a 20% inclusion level in Sarda lamb diets. The current trend towards sustainable production and circular economy models supports the utilization of agro-industrial waste products instead of traditional feedstuffs in order to improve resource use efficiency, with no reduction in the quality of the final animal products (Vastolo et al., 2022; Musati et al., 2023; Shah et al., 2025). The high availability of pistachio processing residues, together with its high content of fermentable carbohydrates, fibre, and polyphenols (including flavonoids, anthocyanins and their related compounds), and their antioxidant properties, supports their potential use as feed ingredients capable of reducing feed costs while improving meat oxidative stability (Tomaino et al., 2010; Shakeri et al., 2017; Arjeh et al., 2020; Koyuncu et al., 2025).

In the present trial, no effect on growth performance and carcass yield, in agreement with previous findings on nut-derived by-products in small ruminants, where moderate inclusion level did not affect growth or feed intake (Ghasemi et al., 2012; SoltaniNezhad et al., 2016). Similarly, pistachio by-product inclusion (up to 30%) has been reported not to impair growth performance while promoting improved antioxidant status and reduced lipid oxidation in lamb meat (Norouzian and Ghiasi, 2012; Noruzi et al., 2024; Kazemi et al., 2024). Comparable results have also been reported for almond hulls, which can be safely included in balanced diets despite their high lignin and fibre content (Scerra et al., 2022; Scerra et al., 2023). A slight deterioration of feed conversion ratio was observed in lambs fed the PH20 diet, likely related to lower digestibility and energy density of fibrous residues, has been previously reported and is consistent with the present findings, underscoring the importance of appropriate diet formulation when high-fibre by-products are used (Recalde et al., 2024; Cachucho et al., 2025; Sırakaya, 2023; Zoabi et al., 2025). Similar benefits on intestinal morphology, antioxidant capacity, rumen fermentation, and methane mitigation have been described following dietary supplementation of pistachio hulls, generally without compromising digestibility (Abid et al., 2019; Hassan et al., 2020). Comparable results with olive cake and citrus pulp further support their role as sustainable feed components in small ruminants (Gravador et al., 2014; Caparra et al., 2023; De Caria et al., 2025).

The increase in muscle ether extract observed in PH20 lambs suggests a modest enhancement of lipid deposition, consistent with responses to almond hulls (Scerra et al., 2022; Scerra et al., 2023), plausibly mediated by plant secondary metabolites that influence rumen fermentation and lipid metabolism (Musati et al., 2023; Shah et al., 2025). In this context, polyphenols-rich agro-industrial by-products have been increasingly recognized as functional feed ingredients capable of modulating lipid metabolism and improving animal performance (Elhadef et al., 2021; Zhao et al., 2023), and pistachio hulls appear to fit within this broader category.

Regarding the fatty acid composition, the higher α-linolenic acid content in PH20 meat likely reflects partial protection of dietary PUFA from ruminal hydrogenation and modulation of microbial lipid metabolism driven by tannins and other polyphenolic compounds in pistachio hulls. These mechanisms have been demonstrated in studies employing tannin-rich feeds or plant extracts that either inhibit specific steps of the biohydrogenation pathway or shift microbial populations toward species associated with incomplete hydrogenation (Vasta and Luciano, 2011; Buccioni et al., 2012; Kahraman et al., 2023; Musati et al., 2025).

The increase in rumenic acid is of nutritional relevance, given its reported beneficial effects on lipid metabolism, inflammation, and oxidative status (Givens, 2010). Its higher concentration in meat from the PH20 group may result from increased formation from vaccenic acid and reduced further hydrogenation to stearic acid. Comprehensive reviews on pistachio by-products confirm that their polyphenolic profile, rich in flavan-3-ols, phenolic acids and condensed tannins, can interact with lipid metabolism and microbial consortia in the rumen, ultimately influencing the pattern of biohydrogenation intermediates (Kahraman et al., 2023). The higher C18:0 levels in PH20 meat are likely attributable to its higher levels in the PH20 diet.

The rise in α-linolenic acid further suggests that pistachio hulls contribute not only as fibre source but also as a carrier of bioactive compounds capable that enhance meat nutritional quality. Similar effects have been observed in lambs fed hazelnut skin or linseed-based diets, where increased α-linolenic acid levels were attributed to reduced ruminal degradation rather than *de-novo* synthesis (Ciliberti et al., 2024; Musati et al., 2024a; Cattivelli et al., 2025).

From a comparative standpoint, almond, hazelnut and pistachio by-products share compositional traits such as residual unsaturated lipid and polyphenols. However, differences in tannin structure, fibre composition, and flavonoid profile likely explain variability in animal responses (Monagas et al., 2009; Arjeh et al., 2020; Ivanović et al., 2020; Koç and Atar Kayabaşi, 2023; Silva et al., 2025). In particular, pistachio by-products used in previous studies often contained mixed fractions (hulls, leaves, and shells) with higher tannin content and lower fermentable carbohydrate availability, which may negatively affect intake and performance at high inclusion levels (Ghaffari et al., 2014; Soltani Nezhad et al., 2016; Cachucho et al., 2024; Recalde et al., 2024). By contrast, the pistachio hulls used in the present study exhibited a more balanced composition, which likely contributed to the absence of negative effects on intake (Ghaffari et al., 2014; Soltani Nezhad et al., 2016).

In ruminants, change in tissue fatty acids composition are inherently limited by rumen biohydrogenation and by the physicochemical properties of dietary lipid, which restrict PUFA transfer to tissues (Chilliard et al., 2007; Sinclair et al., 2005; Chikunya et al., 2004). Within these constraints, the moderate increases in α-linolenic and rumenic acids observed in the present study can nevertheless be considered nutritionally meaningful improvements in meat lipid quality (Cal-Pereyra et al., 2023). The antioxidant responses observed at muscle level further support the potential of pistachio hulls as a functional feed ingredient. Among the secondary compounds generated during lipid peroxidation, malondialdehyde is one of the most abundant and widely used indicators of oxidative deterioration, being measured, along with other reactive aldehydes, by the TBARS assay. Fresh meat from lambs fed the PH20 diet exhibited lower levels of secondary lipid oxidation products than meat from control lambs. Although TBARS values increased during storage in both groups (diet × time interaction), PH20 meat exhibited lower TBARS values than control meat at the final storage time point. On day 7 of refrigerated storage, the control treatment showed 1.99 mg MDA/kg meat, whereas PH20 samples remained below 1.5 mg MDA/kg. Campo et al. (2006) reported 2 mg MDA/kg meat as the sensory threshold for rancid off-flavour perception in fresh meat. Accordingly, TBARS values in control samples approached this threshold, suggesting a potential negative impact on flavour and aroma perception by consumers. The lower MDA formation in meat from the PH20 group, along with stabilized redness and chroma values during storage, are consistent with the antioxidant capacity of pistachio green hull extracts in meat systems, where lipid and pigment oxidation are delayed (Noorolahi et al., 2020). This result was likely due to the increased α-tocopherol content in PH20 meat, which contributed to its superior antioxidant capacity. The α-tocopherol has been extensively studied because it protects membrane fatty acids from lipid peroxidation (Ponnampalam et al., 2022). However, α-tocopherol levels in PH20 meat compared to control meat were unexpectedly higher, considering the α-tocopherol content of the experimental diets. Drawing on data from previous studies regarding the potential influence of polyphenol-rich by-products on nutrient absorption (Viveros et al., 2011; Iglesias et al., 2012; Abu Hafsa and Ibrahim, 2018), we hypothesized that the supplementation of pistachio hulls may have positively influenced vitamin E absorption. Evidence on the effects of dietary polyphenols on meat antioxidant status in ruminants remains inconsistent (Luciano et al., 2011a, b), likely reflecting their structural diversity and limited bioavailability, which constrains intestinal uptake and tissue deposition, as reported for condensed tannins (Soldado et al., 2021). Nonetheless, indirect antioxidant effects have been described. Lobón et al. (2017), for example, found that quebracho tannins increased muscle α-tocopherol and reduced lipid oxidation in lambs, despite unchanged vitamin E intake. In this context, pistachio hulls supplementation may have improved antioxidant status by enhancing tocopherol intake and by limiting their oxidation through polyphenol-mediated protection. The elevated content of polyphenols in pistachio hulls increased the levels of these compounds in the PH20 treatment, resulting in a concentration 3–4 folds higher than in the control treatment. Recent studies conducted by Elakremi et al (2020; 2022) have shown that processing wastes from pistachios exhibit a very high concentration of polyphenolic compounds, and a larger portion of those compounds have significant antioxidant ability. Phenolic acids, anthocyanins and flavonoids have the ability to stabilize membranes and scavenge reactive oxygen species (Bellomo and Fallico, 2007; Hayes et al., 2010). In addition, several studies have emphasized the capacity of polyphenol-rich agro-industrial by-products to enhance the oxidative stability of meat and animal products, thereby improving shelf life and product quality (Scerra et al., 2023; Cifuni et al., 2023; Duncan et al., 2024; Bouzaiene et al., 2024). Likewise, hazelnut skins and almond hulls decreased TBARS and improved oxidative stability in lambs, reflecting their richness in polyphenols and tocopherols (Della Malva et al., 2023; Ciliberti et al., 2024; Musati et al., 2024a; Cachucho et al., 2024; Recalde et al., 2024; Cattivelli et al., 2025).

Another important determinant of consumer acceptance is meat colour. Regarding storage time, almost all investigated parameters were affected over the 7-day period. The colour descriptors exhibited a discoloration pattern consistent with meat browning over time (Faustman et al., 2010), characterized by a decrease in redness (a*) and concomitant increases in yellowness (b*) and hue angle, in agreement with previous studies conducted under similar experimental conditions (Luciano et al., 2019; Scerra et al., 2022; Menci et al., 2023). However, redness (a*) and chroma values in the PH20 group indicate better colour stability and consumer appeal, likely due to the preservation of oxymyoglobin and protection of membrane lipids from peroxidation. In fact, fresh meat from lambs fed the PH20 diet exhibited a tendentially higher redness (a*) value than meat from control lambs. Although redness (a*) values decreased linearly during storage in both groups, PH20 meat exhibited higher values than control meat at the final storage time point (13.6 *vs* 11.8 in PH20 and control groups, respectively). This is in line with evidence for natural carotenoids and polyphenols improving colour stability in beef and poultry products (Bellomo and Fallico, 2007; Hayes et al., 2010; Rajput et al., 2014; Natalello et al., 2020; Terevinto et al., 2023). Similar improvements have been described with almond hulls (Cachucho et al., 2024; Recalde et al., 2024), hazelnut skins (Della Malva et al., 2023; Ciliberti et al., 2024; Musati et al., 2024a; Cattivelli et al., 2025), which enhances redness and mitigates discoloration during storage.

Conclusions

The present study demonstrates that partial replacement of conventional cereals with pistachio hulls at a 20% inclusion level in Sarda lamb diets can be implemented without compromising growth performance or carcass yield. A slight deterioration of feed conversion ratio was observed in lambs fed the PH20 diet, likely related to lower digestibility and energy density of fibrous residues, underscoring the importance of appropriate diet formulation when high-fibre by-products are used. The dietary use of this polyphenol-rich agro-industrial residue selectively modulated meat lipid composition, enhancing rumenic and α-linolenic acids, while maintaining overall fatty acid balance and quality indices. These modifications are consistent with the recognized ability of nut-derived by-products to influence rumen biohydrogenation dynamics and promote the accumulation of health promoting intermediates such as CLA and n-3 fatty acids. In parallel, the observed reduction in lipid peroxidation and the improvement in color vividness confirm the antioxidant efficacy of pistachio hulls.

Taken together, these findings support the feasibility of incorporating pistachio hulls as a functional feed ingredient for small ruminants, offering dual benefits in terms of oxidative stability and nutritional enhancement of meat. The cross-species consistency of antioxidant and lipid responses observed with other nut and fruit residues, such as almond hulls, hazelnut skins, and olive cake, further highlights the robustness of this strategy within circular livestock systems. The valorization of pistachio processing by-products therefore represents a practical route to reduce feed costs, lower environmental impact, and replace synthetic antioxidants with natural alternatives of regional origin.

Acknowledgements

The authors would like to acknowledge Bovicarne Sicilia Soc. Coop. (Gangi, PA) for the technical assistance and the organic farm Di GaLa (San Biagio Platani, AG) for providing the pistachio hull.

Author Contribution Statement

P. De Caria: Writing-Original draft, Final approval of the version to be published; P. Fortugno: Formal analysis, Writing-Review & Editing, Final approval of the version to be published; M. Bognanno: Methodology, Writing-Review & Editing, Final approval of the version to be published; F. Foti: Methodology, Writing-Review & Editing, Final approval of the version to be published; P. Caparra: Writing-Review & Editing, Final approval of the version to be published; C. Cilione: Writing-Review & Editing, Final approval of the version to be published; S. Bognanno: Writing-Review & Editing, Final approval of the version to be published; M. Musati: Formal analysis, Writing-Review & Editing, Final approval of the version to be published; G. Mangione: Formal analysis, Writing-Review & Editing, Final approval of the version to be published; M. Scerra:

Conceptualization, Methodology, Writing-Original draft, Final approval of the version to be published.

Funding

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

References

Abid, K., Jabri, J., Beckers, Y., Yaich, H., Malek, A., Rekhis, J., Kamoun, M., 2019. Effects of exogenous fibrolytic enzymes on the ruminal fermentation of agro-industrial by-products. S. Afr. J. Anim. Sci. 49, 612. https://doi.org/10.4314/sajas.v49i4.2

Alasalvar, C., Salvadó, J.S., Ros, E., 2020. Bioactives and health benefits of nuts and dried fruits. Food Chem. 314, 126192. https://doi.org/10.1016/j.foodchem.2020.126192

AOAC, 1995. Official methods of analysis, 16th ed. Assoc. Off. Anal. Chem., Washington, DC, USA.

Arjeh, E., Akhavan, H.R., Barzegar, M., Carbonell-Barrachina, Á.A., 2020. Bio-active compounds and functional properties of pistachio hull: A review. Trends Food Sci. Technol. 97, 55–64. https://doi.org/10.1016/j.tifs.2019.12.031

Barone, E., Marra, F.P., 2004. The pistachio industry in Italy: Current situation and prospects. Report.

Bellomo, M. G., Fallico, B., 2007. Anthocyanins, chlorophylls and xanthophylls in pistachio nuts (Pistacia vera) of different geographic origin. J. Food Compos. Anal. 20(3), 352-359. https://doi.org/10.1016/j.jfca.2006.04.002

Bertolín, J. R., Joy, M., Rufino-Moya, P. J., Lob´on, S., Blanco, M., 2018. Simultaneous determination of carotenoids, tocopherols, retinol and cholesterol in ovine lyophilised samples of milk, meat, and liver and in unprocessed/raw samples of fat. Food Chem. 257, 182–188. https://doi.org/10.1016/j.foodchem.2018.02.139

Bešlo, D., Došlić, G., Agić, D., Rastija, V., Šperanda, M., Gantner, V., Lučić, B., 2022. Polyphenols in ruminant nutrition and their effects on reproduction. Antioxidants 11, 970. https://doi.org/10.3390/antiox11050970

Bouzaiene, A., Mansour, R.B., Jemaa-Guirat, M.B., Hammami, I., Trabelsi, D., Msaada, K., Labidi, N., 2024. Exploring the bioactive potential of dried fruit by-products: a focus on hazelnut, peanut, and almond teguments and shells. Int. J. Environ. Health Res. 35, 864–877. https://doi.org/10.1080/09603123.2024.2373174

Buccioni, A., Decandia, M., Minieri, S., Molle, G., Cabiddu, A., 2012. Lipid metabolism in the rumen: New insights on lipolysis and biohydrogenation with an emphasis on the role of endogenous plant factors. Anim. Feed Sci. Technol. 174, 1–25. https://doi.org/10.1016/j.anifeedsci.2012.02.009

Cachucho, L., Alves, S.P., Varregoso, M., Costa, C., Paulos, K., Almeida, J.M., Soldado, D., Guerreiro, O., Bessa, R.J.B., Santos-Silva, J., Dentinho, M.T.P., Jerónimo, E., 2025. Use of almond hulls in lamb diets – Effects on growth performance and carcass and meat quality. Meat Sci. 221, 109733. https://doi.org/10.1016/j.meatsci.2024.109733

Cal-Pereyra, L., González-Montaña, J. R., Neimaur Fernández, K., Abreu-Palermo, M. C., Martín Alonso, M. J., Velázquez-Ordoñez, V., Acosta-Dibarrat, J., 2023. Effects of Ewe's Diet Supplementation with Polyunsaturated Fatty Acids on Meat Lipid Profile of Suckling Lambs. Agriculture 13(3), 710. https://doi.org/10.3390/agriculture13030710

Campo, M. M., Nute, G. R., Hughes, S. I., Enser, M., Wood, J. D., Richardson, R. I., 2006. Flavour perception of oxidation in beef. Meat Sci. 72(2), 303–311. https://doi.org/10.1016/j.meatsci.2005.07.015

Cannas, A., Tedeschi, L., Fox, D., Pell, A.N., Van Soest, P., 2004. A mechanistic model for predicting the nutrient requirements and feed biological values for sheep. J. Anim. Sci. 82, 149–169. https://doi.org/10.2527/2004.821149x.

Caparra, P., Chies, L., Scerra, M., Foti, F., Bognanno, M., Cilione, C., De Caria, P., Claps, S., Cifuni, G.F., 2023. Effect of dietary ensiled olive cake supplementation on performance and meat quality of Apulo-Calabrese pigs. Animals 13, 2022. https://doi.org/10.3390/ani13122022

Cattivelli, A., Zannini, M., D'Ambra, K., Trovato, R., Minelli, G., Musati, M., Luciano, G., Priolo, A., Natalello, A., Conte A., Tagliazucchi D., Fiego, D. P. L., 2025. Feeding lambs hazelnut skin and linseed decreases meat lipid oxidation during in vitro digestion. Food Chem. 483, 144266. https://doi.org/10.1016/j.foodchem.2025.144266

Chikunya, S., Demirel, G., Enser, M., Wood, J. D., Wilkinson, R. G., Sinclair, L. A., 2004. Biohydrogenation of dietary n-3 PUFA and stability of ingested vitamin E in the rumen, and their effects on microbial activity in sheep. Br. J. Nutr. 91(4), 539–550. https://doi.org/10.1079/bjn20031078

Chilliard, Y., Glasser, F., Ferlay, A., Bernard, L., Rouel, J., Doreau, M., 2007. Diet, Rumen Biohydrogenation and Nutritional Quality of Cow and Goat Milk Fat. Eur. J. Lipid Sci. Technol. 109, 828-855. https://doi.org/10.1002/ejlt.200700080

Chiofalo, V., Liotta, L., Lo Presti, V., Gresta, F., Di Rosa, A.R., Chiofalo, B., 2020. Effect of dietary olive cake supplementation on performance, carcass characteristics, and meat quality of beef cattle. Animals 10, 1176. https://doi.org/10.3390/ani10071176

Cifuni, G.F., Clap,s S., Morone, G., Sepe, L., Caparra, P., Benincasa, C., Pellegrino, M., Perri, E., 2023. Valorization of olive mill byproducts: Recovery of biophenol compounds and application in animal feed. Plants 12, 3062. https://doi.org/10.3390/plants12173062

Ciliberti, M. G., Santillo, A., Caroprese, M., Della Malva, A., Natalello, A., Bertino, A., Albenzio, M., Sevi, A., 2024. Role of hazelnut skin supplementation on plasma antioxidant status and cytokine profile in growing lambs. Front. Vet. Sci. 2024, 11, 1340141. https://doi.org/10.3389/fvets.2024.1340141

De Caria, P., Chies, L., Cifuni, G.F., Scerra, M., Foti, F., Cilione, C., Fortugno, P., Boninsegna, M.A., Giacondino, C., Claps, S., et al., 2025. The effects of olive cake and linseed dietary supplementation on the performance, carcass traits, and oxidative stability of beef from young Podolian bulls. Animals 15, 2188. https://doi.org/10.3390/ani15152188

Della Malva, A., Santillo, A., Priolo, A., Marino, R., Ciliberti, M. G., Sevi, A., Albenzio, M., 2023. Effect of hazelnut skin by-product supplementation in lambs' diets: implications on plasma and muscle proteomes and first insights on the underlying mechanisms. J. proteom. 271, 104757. https://doi.org/10.1016/j.jprot.2022.104757

Duncan, Z.M., DeBord, Z.L., Pflughoeft, M.G., Suhr, K.J., Hollenbeck, W.R., Brazle, F.K., Wecker, H.K., Paulk, C.B., Titgemeyer, E.C., Olson, K.C., Blasi, D.A., 2024. Almond hulls and shells as an alternative fiber source in limit-fed growing beef cattle diets. Transl. Anim. Sci. 8, txae025. https://doi.org/10.1093/tas/txae025

Elakremi, M., Sillero, L., Ayed, L., Labidi, J., Moussaoui, Y., 2020. Chemical Composition of Leaves and Hull from Pistacia Vera L. an Evaluation of Phenolic Content and Antioxidant Properties of their Extracts. Research square. https://doi.org/10.21203/rs.3.rs-128147/v1

Elakremi, M., Sillero, L., Ayed, L., Mosbah, M. B., Labidi, J., Ben Salem, R., Moussaoui, Y., 2022. Pistacia vera L. leaves as a renewable source of bioactive compounds via microwave assisted extraction. Sustain. Chem. Pharm. 29, 100815. https://doi.org/10.1016/j.scp.2022.100815

Elhadef, K., Ennouri, K., Fourati, M., Ben Hlima, H., Akermi, S., Mellouli, L., Smaoui, S., 2021. Pistachio hull extract as a practical strategy to extend the shelf life of raw minced beef: Chemometrics in quality evaluation. Evid. Based Complement. Alternat. Med., 2429766. https://doi.org/10.1155/2021/2429766

FAOSTAT, 2022. FAOSTAT Data of Crops and Livestock Products. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. Available at: https://www.fao.org/faostat/en/#data

Faustman, C., Sun, Q., Mancini, R., Suman, S. P., 2010. Myoglobin and lipid oxidation interactions: Mechanistic bases and control. Meat Sci. 86, 86–94. https://doi. org/10.1016/j.meatsci.2010.04.025

Folch, J., Lees, M., Sloane Stanley, G.H., 1957. A simple method for the isolation and purification of total lipids from animal tissues. J. Biol. Chem. 226, 497–509. https://doi.org/10.1016/S0021-9258(18)64849-5

Givens, D.I., 2010. Milk and meat in our diet: good or bad for health?. Animal 4 (12), 1941-1952. https://doi.org/10.1017/S1751731110001503.

Gentile, C., Tesoriere, L., Butera, D., Fazzari, M., Monastero, M., Allegra ,M., Livrea, M.A., 2007. Antioxidant activity of Sicilian pistachio (Pistacia vera L. var. Bronte) nut extract and its bioactive components. J. Agric. Food Chem. 55, 643–648. https://doi.org/10.1021/jf062533i

Ghaffari, M. H., Tahmasbi, A. M., Khorvash, M., Naserian, A. A., Ghaffari, A. H., Valizadeh, H., 2014. Effects of pistachio by-products in replacement of alfalfa hay on populations of rumen bacteria involved in biohydrogenation and fermentative parameters in the rumen of sheep. J. Anim. Physiol. Anim. Nutr. 98(3), 578–586. https://doi.org/10.1111/jpn.12120

Ghasemi, S., Naserian, A.A., Valizadeh, R., Tahmasebi, A.M., Vakili, A.R., Behgar, M., Ghovvati, S., 2012. Inclusion of pistachio hulls as a replacement for alfalfa hay in the diet of sheep causes a shift in the rumen cellulolytic bacterial population. Small Rumin. Res. 104, 94–98. https://doi.org/10.1016/j.smallrumres.2011.09.052

Godfray, H.C.J., Beddington, J.R., Crute, I.R., 2010. Food security: The challenge of feeding 9 billion people. Science 327, 812–818. https://doi.org/10.1126/science.1185383

Gravador, R.S., Jongberg, S., Andersen, M.L., Luciano, G., Priolo, A., Lund, M.N., 2014. Dietary citrus pulp improves protein stability in lamb meat stored under aerobic conditions. Meat Sci. 97, 231–236. https://doi.org/10.1016/j.meatsci.2014.01.016

Gray, I.K., Rumsby, M.G., Hawke, J.C., 1967. The variations in linolenic acid and galactolipid levels in Graminaceae species with age of tissue and light environment. Phytochemistry 6, 107–113. https://doi.org/10.1016/0031-9422(67)85014-3

Hassan, F.U., Arshad, M.A., Ebeid, H.M., Rehman, M.S., Khan, M.S., Shahid, S., Yang, C., 2020. Phytogenic additives can modulate rumen microbiome to mediate fermentation kinetics and methanogenesis through exploiting diet–microbe interaction. Front. Vet. Sci. 7, 575801. https://doi.org/10.3389/fvets.2020.575801

Hayes, J. E., Stepanyan, V., Allen, P., O'grady, M. N., Kerry, J. P., 2010. Effect of lutein, sesamol, ellagic acid and olive leaf extract on the quality and shelf-life stability of packaged raw minced beef patties. Meat sci. 84(4), 613-620. https://doi.org/10.1016/j.meatsci.2009.10.020

IUPAC, 1987. Standard methods for the analysis of oils, fats and derivatives, 7th ed. Blackwell Scientific Publications, Oxford, UK.

Iglesias, J., Pazos, M., Torres, J.L., Medina, I., 2012. Antioxidant mechanism of grape procyanidins in muscle tissues: Redox interactions with endogenous ascorbic acid and α-tocopherol. Food Chem. 134, 1767–1774. 10.1016/j.foodchem.2012.03.072

Ivanović, S., Avramović, N., Dojčinović, B., Trifunović, S., Novaković, M., Tešević, V., Mandić, B., 2020. Chemical Composition, Total Phenols and Flavonoids Contents and

Antioxidant Activity as Nutritive Potential of Roasted Hazelnut Skins (Corylus avellana L.). Foods 9(4), 430. https://doi.org/10.3390/foods9040430

Kahraman, M., Yurtseven, S., Sakar, E., Daş, A., Yalçın, H., Güngören, G., Boyraz, M.Ü., Koyuncu, İ., 2023. Pistachio, Pomegranate and Olive Byproducts Added to Sheep Rations Change the Biofunctional Properties of Milk through the Milk Amino Acid Profile. Food Sci. Anim. Resour. 43(1), 124-138. https://doi.org/10.5851/kosfa.2022.e65

Kazemi, M., Valizadeh, R., Salem, A.Z.M., 2024. Dietary inclusion of pistachio wastes (Pistacia vera L.) to fattening male goat kids' feeding: Chemical-mineral compositions, in vitro ruminal fermentation, in vivo digestibility, hemato-biochemical profile, and growth performance. Small Rumin. Res. 235, 107274. https://doi.org/10.1016/j.smallrumres.2024.107274

Koç, B., Atar Kayabaşi, G., 2023. Enrichment of White Wheat Bread with Pistachio Hulls and Grape Seeds: Effect on Bread Quality Characteristics. Applied Sci. 13(6), 3431. https://doi.org/10.3390/app13063431

Koyuncu, I., Temiz, E., Yüksekdag, O., Egi, K., Cakmak, Y., Zengin, G., 2025. From waste to wealth: Pistachio green hulls as a novel source of antioxidants and dietary supplements. Waste Biomass Valor. 16, 6741-6759. https://doi.org/10.1007/s12649-025-03055-z

Lobon, S., Sanz, A., Blanco, M., Ripoll, G., Joy, M., 2017. The type of forage and condensed tannins in dams' diet: Influence on meat shelf life of their suckling lambs. Small Rumin. Res. 154, 115–122. https://doi.org/10.1016/j. smallrumres.2017.08.005.

López-Andrés, P., Luciano, G., Vasta, V., Gibson, T.M., Scerra, M., Biondi, L., Priolo, A., Mueller-Harvey, I., 2014. Antioxidant effects of ryegrass phenolics in lamb liver and plasma. Animal 8, 51–57. https://doi.org/10.1017/S1751731113001821.

Luciano, G., Moloney, A. P., Priolo, A., R¨ohrle, F. T., Vasta, V., Biondi, L., … Monahan, F. J., 2011. Vitamin E and polyunsaturated fatty acids in bovine muscle and the oxidative stability of beef from cattle receiving grass or concentrate-based rations. J. Anim. Sci. 89(11), 3759–3768. https://doi.org/10.2527/ jas.2010-3795

Luciano, G., Pauselli, M., Servili, M., Mourvaki, E., Serra, A., Monahan, F.J., Lanza, M., Priolo, A., Zinnai, A., Mele, M., 2013. Dietary olive cake reduces the oxidation of lipids, including cholesterol, in lamb meat enriched in polyunsaturated fatty acids. Meat Sci. 93, 703–714. https://doi.org/10.1016/j.meatsci.2012.11.033

Luciano, G., Natalello, A., Mattioli, S., Pauselli, M., Sebastiani, B., Niderkorn, V., Copani, G., Benhissi, H., Amanpour, A., Valenti, B., 2019. Feeding lambs with silage mixtures of grass, sainfoin and red clover improves meat oxidative stability under high oxidative challenge. Meat Sci. 156, 59–67. https://doi.org/10.1016/ j.meatsci.2019.05.020

Makkar, H.P., Blümmel, M., Borowy, N.K., Becker, K., 1993. Gravimetric determination of tannins and their correlations with chemical and protein precipitation methods. J. Sci. Food Agric. 61, 161–165. https://doi.org/10.1002/jsfa.2740610205.

Makkar, H.P.S., Francis, G., Becker, K., 2007. Bioactivity of phytochemicals in some lesser-known plants and their effects and potential applications in livestock and aquaculture production systems. Animal 1, 1371-1391. https://doi.org/10.1017/S1751731107000298.

Menci, R., Khelil-Arfa, H., Blanchard, A., Biondi, L., Bella, M., Priolo, A., Luciano, G., Natalello, A., 2022. Effect of dietary magnolia bark extract supplementation in finishing pigs on the oxidative stability of meat. J. Anim. Sci. Biotech. 13, 89. https://doi.org/10.1186/s40104-022-00740-0.

Menci, R., Biondi, L., Natalello, A., Lanza, M., Priolo, A., Valenti, B., Bertino, A., Scerra, M., Luciano, G., 2023. Feeding hazelnut skin to lambs delays lipid oxidation in meat. Meat Sci. 202, 109218. https://doi.org/10.1016/j.meatsci.2023.109218.

Min B.R., Barry, T.N., Attwood, G.T., McNabb, W.C., 2003. The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages: a review. Anim. Feed Sci. Technol. 106, 3-19. https://doi.org/10.1016/S0377-8401(03)00041-5.

Min, B.R., Attwood, G.T., McNabb, W.C., Molan, A.L., Barry, T.N., 2005. The effect of condensed tannins from Lotus corniculatus on the proteolytic activities and growth of rumen bacteria. Anim, Feed Sci. Technol. 121:45-58. https://doi.org/10.1016/j.anifeedsci.2005.02.007.

Monagas, M., Garrido, I., Lebrón-Aguilar, R., Gómez-Cordovés, M. C., Rybarczyk, A., Amarowicz, R., Bartolomé, B., 2009. Comparative flavan-3-ol profile and antioxidant capacity of roasted peanut, hazelnut, and almond skins. J. Agric. food Chem. 57(22), 10590–10599. https://doi.org/10.1021/jf901391a.

Musati, M., Menci, R., Luciano, G., Frutos, P., Priolo, A., Natalello, A., 2023. Temperate nuts by-products as animal feed: A review. Anim. Feed Sci. Technol. 305, 115787. https://doi.org/10.1016/j.anifeedsci.2023.115787

Musati, M., Frutos, P., Bertino, .,… et al., 2024a. Dietary combination of linseed and hazelnut skin as a sustainable strategy to enrich lamb with health promoting fatty acids. Sci. Rep. 14, 10133. https://doi.org/10.1038/s41598-024-60303-3

Musati, M., Hervas, G., Natalello, A., Toral, P. G., Luciano, G., Priolo, A., Frutos, P., 2024b. Could we partially replace maize with nut skins for more sustainable sheep diets? In vitro ruminal fermentation and biohydrogenation. Anim. Feed Sci.Technol. 318, 116113. https://doi.org/10.1016/j.anifeedsci.2024.116113.

Musati, M., Bella, M. S., Bertino, A., Mangano, F., Luciano, G., Priolo, A., Biondi L., Lanza M., Solarczyk P., Mangione G., Natalello A., 2025. Pistachio skin as a novel feedstuff for lambs: effects on growth performance and meat quality. Anim. Feed Sci. Technol., 116534. https://doi.org/10.1016/j.anifeedsci.2025.116534.

Natalello, A., Priolo, A., Valenti, B., Codini, M., Mattioli, S., Pauselli, M., Puccio, M., Lanza, M., Stergiardis, S., Luciano, G., 2020. Dietary pomegranate by-product improves oxidative stability of lamb meat. Meat Sci. 162, 108037. https://doi.org/10.1016/j.meatsci.2019.108037.

Natalello, A., Khelil-Arfa, H., Luciano, G., Zoon, M., Menci, R., Scerra, M., Blanchard, A., Mangano, F., Biondi, L., Priolo, A., 2022. Effect of different levels of organic zinc supplementation on pork quality. Meat Sci. 186, Article 108731. https://doi.org/ 10.1016/j.meatsci.2021.108731.

Noorolahi, Z., Sahari, M. A., Barzegar, M., Ahmadi Gavlighi, H., 2020. Tannin fraction of pistachio green hull extract with pancreatic lipase inhibitory and antioxidant activity. J. Food Biochem. 44(6), e13208. https://doi.org/10.1111/jfbc.13208

Norouzian, M.A., Ghiasi, S.E., 2012. Carcass performance and meat mineral content in Balouchi lamb fed pistachio by-products. Meat Sci. 92, 157–159. https://doi.org/10.1016/j.meatsci.2012.04.003

Noruzi, H., Aziz-Aliabadi, F., Imari, Z.K., 2024. Effects of different levels of pistachio (Pistacia vera) green hull aqueous extract on performance, intestinal morphology and antioxidant capacity in *Eimeria*-challenged broilers. Poult. Sci. 103, 103667. https://doi.org/10.1016/j.psj.2024.103667

Ponnampalam, E. N., Kiani, A., Santhiravel, S., Holman, B. W. B., Lauridsen, C., Dunshe, F. R., 2022. The importance of dietary antioxidants on oxidative stress, meat and Milk production, and their preservative aspects in farm animals: Antioxidant action, animal health, and product quality—Invited review. Animals, 12 (23), 3279. https://doi.org/10.3390/ani12233279

Rajput, N., Ali, S., Naeem, M., Khan, M. A., Wang, T., 2014. The effect of dietary supplementation with the natural carotenoids curcumin and lutein on pigmentation, oxidative stability and quality of meat from broiler chickens affected by a coccidiosis challenge. Br. Poult. Sci. 55(4), 501-509. https://doi.org/10.1080/00071668.2014.925537

Recalde, A., Evan, T.D., Fernández, C., Roldán, R.A., López-Feria, S., Carro, M.D., 2024. Chemical composition and nutritive value of almond hulls from two almond varieties and influence of including almond hulls in the diet on in vitro ruminal fermentation and methane production. Vet. Sci. 11, 242. https://doi.org/10.3390/vetsci11060242

Routray, W., Orsat, V., 2017. Plant by-products and food industry waste: A source of nutraceuticals and biopolymers. In: Food Bioconversion. Academic Press, pp. 279–315. https://doi.org/10.1016/B978-0-12-811413-1.00008-5

Rufino-Moya, P. J., Joy, M., Lob´on, S., Bertolín, J. R., Blanco, M., 2020. Carotenoids and liposoluble vitamins in the plasma and tissues of light lambs given different maternal feedings and fattening concentrates. Animals 10, 1813. https://doi.org/10.3390/ani10101813

Salami, S.A., Luciano, G., O'Grady, M.N., Biondi, L., Newbold, C.J., Kerry, J.P., Priolo, A., 2019. Sustainability of feeding plant by-products: A review of the implications for ruminant meat production. Anim. Feed Sci. Technol. 251, 37–55. https://doi.org/10.1016/j.anifeedsci.2019.02.006

Scerra, M., Foti, F., Caparra, P., Cilione, C., Violi, L., Fiammingo, G., D'Agui', G., Chies, L., 2018. Effects of feeding fresh bergamot (citrus Bergamia Risso) pulp at up to 35% of dietary dry matter on growth performance and meat quality from lambs. Small Rumin. Res. 169, 160–166. https://doi.org/10.1016/j.smallrumres.2018.09.016.

Scerra, M., Bognanno, M., Foti, F., Caparra, P., Cilione, C., De Caria, P., Fortugno, P., Luciano, G., Natalello, A., Chies, L., 2023. Effect of high levels of almond hulls supplementation on performance and meat oxidative stability in lambs. Meat Sci. 205, 109295. https://doi.org/10.1016/j.meatsci.2023.109295

Scerra, M., Bognanno, M., Foti, F., Caparra, P., Cilione, C., Mangano, F., Natalello, A., Chies, L., 2022. Influence of almond hulls in lamb diets on animal performance and meat quality. Meat Sci. 192, 108903. https://doi.org/10.1016/j.meatsci.2022.108903

Scerra, M., Foti F., Caparra, P., Cilione, C., Bognanno, M., Fortugno, P., De Caria, P., Natalello, A., Musati, M., Chies, L., 2024. Effects of feeding bergamot pulp and olive leaves on performance and meat quality in Apulo-Calabrese pigs. Vet. Anim. Sci. 23, 100336. https://doi.org/10.1016/j.vas.2024.100336

Scerra, M., Foti, F., Caparra, P., Lanza, M., Natalello, A., Cilione, C., Rao, R., D'Aguì, G., Chies, L., 2021. The effect of fresh bergamot pulp on fatty acid composition of suckling kids. Small Rumin. Res. 203, 106483. https://doi.org/10.1016/j.smallrumres.2021.106483

Silva, V., Oliveira, I., Pereira, J.A., Gonçalves, B., 2025. Almond by-products: A comprehensive review of composition, bioactivities, and influencing factors. Foods 14, 1042. https://doi.org/10.3390/foods14061042

Shah, A.M., Zhang, H., Shahid, M., Ghazal, H., Shah, A.R., Niaz, M., Naz, T., Ghimire K., Goswami N., Shi W., et al., 2025. The vital roles of agricultural crop residues and agro-industrial by-products to support sustainable livestock productivity in subtropical regions. Animals 15, 1184. https://doi.org/10.3390/ani15081184

Shakeri, P., Hoseini Ghafari, M., Fazaeli, H., 2017. Pistachio by-product as a forage source for ruminant nutrition: A review (Part B: Ammonia, microbial protein synthesis, fermentation, and biohydrogenation in the rumen, methane, and blood metabolites). Res. J. Livest. Sci. 29, 99–110. https://doi.org/10.22092/asj.2017.109467

Simitzis, P.E., Deligeorgis, S.G., 2018. Agroindustrial by-products and animal products: A great alternative for improving food-quality characteristics and preserving human health. In: *Food Quality: Balancing Health and Disease*. Academic Press, 253–290. https://doi.org/10.1016/B978-0-12-811442-1.00008-0

Sinclair, L.A., Cooper, S.L., Chikunya, S.,….et al., 2025. Biohydrogenation of n-3 polyunsaturated fatty acids in the rumen and their effects on microbial metabolism and plasma fatty acid concentrations in sheep. Animal Sci. 81(2), 239-248. https://doi.org/10.1079/ASC50040239

Sırakaya, S., 2023. Chemical, nutritive, fermentative and microbial composition of almond hull silage. J. Appl. Anim. Res. 51, 17–23. https://doi.org/10.1080/09712119.2022.2148678

Siu, G.M., Draper, H.H., 1978. A survey of the malonaldehyde content of retail meats and fish. J. Food Sci. 43, 1147–1149. https://doi.org/10.1111/j.1365-2621.1978.tb15256.x

Soldado, D., Bessa, R. J. B., Jer´onimo, E., 2021. Condensed tannins as antioxidants in ruminants—Effectiveness and action mechanisms to improve animal antioxidant status and oxidative stability of products. Animals 11, 11. https://doi. org/10.3390/ani11113243

Soltani Nezhad, B., Dayani, O., Khezri, A., Tahmasbi, R., 2016. Performance and carcass characteristics in fattening lambs fed diets with different levels of pistachio by-products silage with wasted date. Small Rumin. Res. 137, 177–182. https://doi.org/10.1016/j.smallrumres.2016.03.015

Terevinto, A., Cabrera, M.C., Zaccari, F., Saadoun, A., 2023. The Oxidative and Color Stability of Beef from Steers Fed Pasture or Concentrate during Retail Display. Animals 13, 2972. https://doi.org/10.3390/ani13182972

Van Soest, P.J., Robertson, J.B., Lewis, B.A., 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74, 3583–3597. https://doi.org/10.3168/jds.S0022-0302(91)78551-2

Vastolo, A., Calabrò, S., Cutrignelli, M.I., 2022. A review on the use of agro-industrial co-products in animals' diets. Ital. J. Anim. Sci. 21, 577–594. https://doi.org/10.1080/1828051X.2022.2039562.

Waghorn, G.C., Ulyatt, M.J., John, A., Fisher, M.T., 1987. The effect of condensed tannins on the site of digestion of amino acids and other nutrients in sheep fed on Lotus corniculatus L. Br. J. Nutr. 57,115-126. 10.1079/bjn19870015.

Zhao, J., Wang, X., Lin, H., Lin, Z., 2023. Hazelnut and its by-products: A comprehensive review of nutrition, phytochemical profile, extraction, bioactivities and applications. Food Chem. 413, 135576. https://doi.org/10.1016/j.foodchem.2023.135576

Zoabi, H., Ammar, H., Ghzayel, S., Aziz, B.A., Kholif, A.E., Díaz, A., de Haro-Martí, M., Chahine, M., López, S., 2025. Feeding sodium hydroxide-treated almond hulls to Assaf sheep:

Effects on chemical composition, nutrient digestibility, and zootechnical performance. Agriculture 15, 1000. https://doi.org/10.3390/agriculture15091000

Table 1. Ingredients (% on DM basis) and chemical composition of the experimental diets.

	Pistachio hulls	Dietary treatment[1]	
		Control	PH20
Ingredients, % as fed basis			
Maize		30	18
Barley		30	18
Fava bean		20	24
Bran		17	17
Pistachio hulls		-	20
Vitamin mineral premix [2]		3	3
Chemical composition			
Dry matter (DM; g/kg wet weight)	923	913	912
Crude protein (g/kg DM)	97.0	169	168
Ether extract (g/kg DM)	56.7	23.3	26.1
Ash (g/kg DM)	149	53.6	58.4
Neutral detergent fiber (NDF; g/kg DM)	316	269	306
Metabolizable energy (MJ/kg DM)	-	11.3	11.0
Total extractable polyphenols (mg Tae [3]/g DM)	37.6	1.48	4.01
α-Tocopherol (µg/g DM)	10.90	13.5	13.3
Fatty acids (g/100g of total fatty acid)			
C12:0	0.17	0.16	0.16
C14:0	0.43	0.20	0.24
C16:0	18.9	19.2	18.8
C18:0	7.25	2.60	3.00
C18:1 n-9	35.0	24.6	25.8
C18:2 n-6	17.2	45.1	37.2
C18:3 n-3	3.00	1.84	2.48

[1]Control: maize-barley-fava bean based concentrate diet. PH20: diet including 20 % of pistachio hulls.

[2] The mineral vitamin premix consisted of vitamin A=6750 UI; vitamin D3=1000UI; vitamin E 2 mg; vitamin B12 0,01 mg; vitamin B1 1mg; folic acid 0,2 mg; D-pantotenic acid 5 mg; Co 0,05 mg; Mn 12,5 mg; Zn 15 mg; Mo 0,5mg.

[3] Tannic acid equivalents.

Table 2

Animal performance and chemical composition of muscle (g/100g wet weight).

	Dietary treatment[1]		SEM[6]	*P* value
	Control	PH20		
Final BW[2], kg	40.2	39.0	1.370	0.127
Carcass weight, g	17.7	16.9	0.695	0.441
DMI[3], g/d	909	898	8.000	0.499
ADG[4], g/d	223	198	6.760	0.069
FCR[5], g DMI[3]/g ADG[4]	4.10	4.50	0.161	0.049
Chemical composition				
α-Tocopherol, µg/g muscle	0.535	0.659	0.019	0.001
Moisture	74.3	74.2	0.400	0.951
Crude protein	20.8	20.9	0.129	0.943
Ether extract	2.17	2.40	0.039	0.001
Ash	1.07	1.08	0.013	0.636

[1] Control: maize-barley-fava bean based concentrate diet. PH20: diet including 20 % of pistachio hulls.

[2]BW=Body weight; [3]DMI=dry matter intake;[4]ADG=averange daily gain;[5]FCR=feed conversion ratio;[6]SEM= standard error of means.

Table 3

Effect of the dietary treatments on fatty acid composition of muscle (mg/100 g of meat)

	Dietary Treatment[1]			
Item	Control	PH20	SEM[3]	*P* values
intramuscular fat, mg/100 g of muscle	1997	2198	142	0.032
C12:0	0.07	0.08	0.009	0.802
C14:0	1.30	1.60	0.119	0.338
C15:0 *iso*	0.10	0.06	0.004	0.323
C15:0 *anteiso*	0.10	0.07	0.005	0.485
C14:1 *cis-9*	0.05	0.05	0.005	0.821
C16:0	19,0	21,0	0.719	0.116
C17:0 *iso*	0.38	0.37	0.021	0.960
C16:1 *cis-9*	1.38	1.36	0.047	0.823
C17:0	0.87	0.98	0.029	0.056
C18:0	14.1	15.8	0.416	0.036
C18:1 *cis-9*	32.0	35.1	1160	0.196
C18:1 *trans-9*	0.16	0.24	0.016	0.009
C18:1 *trans-11*	0.65	0.77	0.039	0.057
C18:2 *cis-9, cis-12* LA[2]	10.7	8.06	0.847	0.127
C18:3 n-3 ALA[2]	0.11	0.25	0.008	0.049
C18:2 *cis-9 trans-11*	0.32	0.44	0.022	0.005
C 20:1 *cis-11*	0.50	0.41	0.039	0.264
C20:2 *cis 11,14*	0.29	0.08	0.114	0.387
C20:3 n-6	0.34	0.25	0.026	0.112
C20:4 n-6	4.82	3.71	0.454	0.235
C20:5 n-3 EPA[2]	0.28	0.22	0.045	0.518
C22:4 n-6	0.39	0.35	0.029	0.550
C22:5 n-6	0.15	0.13	0.014	0.337
C22:5 n-3 DPA[2]	0.60	0.56	0.061	0.734
C22:6 n-3 DHA[2]	0.21	0.15	0.040	0.465
∑ n-6	16.7	12.6	1.410	0.156
∑ n-3	1.21	1.17	0.127	0.620
n-6/n-3	14.8	10.7	0.875	0.109
∑ SFA[2]	35.5	39.8	1.160	0.058
∑ MUFA[2]	34.8	37.9	1.160	0.182
∑ PUFA[2]	18.2	14.2	1.500	0.101

[1] Control: maize-barley-fava bean based concentrate diet. PH20: diet including 20 % of pistachio hulls.

[2]LA: linoleic acid; ALA: α-linolenic acid; EPA: eicosapentaenoic acid; DPA: docosapentaenoic acid; DHA: docosahexaenoic acid; SFA: saturated fatty acids; MUFA: monounsaturated fatty acids; PUFA: polyunsaturated fatty acids.

[3]SEM= Standard error of the mean.

Table 4

Effect of the dietary treatments and time of refrigerated storage on meat colour stability

	Dietary treatment[1]		Time (T)[3]			SEM[4]	*P* values		
	Control	PH20	0	1	2		Diet	Time	Diet x Time
L* values[2]	41.9	42.5	40.4^{c}	42.51^{b}	43.73^{a}	0.276	0.206	< 0.001	0.135
a* values[2]	14.3	14.9	16.0^{a}	15.1^{a}	12.7^{b}	0.242	0.052	< 0.001	0.025
b* values[2]	12.1	12.8	10.6^{c}	12.6^{b}	14.1^{a}	0.271	0.067	< 0.001	0.561
C* values[2]	18.9	19.7	19.2	19.6	19.1	0.178	0.014	0.382	0.119
H* values[2]	40.4	40.4	33.5^{c}	39.8^{b}	47.91^{a}	0.947	0.985	< 0.001	0.075
TBARS[5]	1.77	1.26	0.27^{c}	1.69^{b}	2.59^{a}	0.148	0.023	< 0.001	0.004

^{a,b,c} Within row, different superscripts indicate differences between days of storage ($P<0.05$) tested using the Tukey's adjustment for multiple comparisons.

[1]Control: maize-barley-fava bean based concentrate diet. PH20: diet including 20 % of pistachio hulls

[2]L*=lightness; a*=redness; b*=yellowness; C*=Chrome; h*=hue angle, measured in degrees.

[3]Times 0, 1, 2 = days 0, 4, 7 for raw meat at 4 °C under aerobic conditions (meat slices).

[4]SEM= Standard error of the mean.

[5]TBARS: thiobarbituric acid reactive substances (mg of malondialdehyde per kg of meat).