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Review article

Temperate nuts by-products as animal feed: A review

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A R T I C L E I N F O

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A B S T R A C T

Using agro-industrial by-products in replacement of conventional feedstuff is a strategy to reduce the environmental impact of feed production and transport, and the feed-food competition. This article reviews the effects of feeding nuts by-products on digestion, metabolism, and product quality in ruminant and monogastric animals. In particular, it focuses on nuts from temperate climate (mainly almond, pistachio, hazelnut, and walnut). These crops produce a variety of by-products of potential interest: hulls, skins (perisperm), oil cake, or mixtures of them. Nuts by-products generally have a low moisture content, making them easy to handle and store. They also contain moderate to high levels of phenolic compounds, which on the one hand have anti-nutritional properties, but on the other hand may exert positive effects on animal health and product quality. The composition of nuts by-products varies considerably from one species to another and within the same species, depending on variety, climatic and agronomic conditions, and processing. This, in combination with a lack of knowledge on production volumes, limits the current use of nuts by-products as animal feed to the farm level. However, some general considerations can be drawn. Almond hulls are rich in digestible fibre and can be used as energy feed for ruminants at doses up to 250 g/kg (dry matter basis). Nuts oil cake can partly replace soybean meal as protein sources for monogastric animals, giving due attention to dietary fibre, essential amino acids, and antinutritional factors such as tannins. Hazelnut skin is particularly rich in unsaturated fatty acids, tocopherols, and phenolic compounds, thus showing the ability to improve the fatty acid profile and antioxidant capacity of animal products. Some nuts by-products, such as chestnut by-products or cull nuts, have not yet been tested in animal nutrition. Further research on the use of these alternative by-products as animal feed is essential to expand the available knowledge and improve the resilience of livestock systems.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC, 2020) highlights that 23% of greenhouse gas emissions from human

Abbreviations: ADF, acid detergent fibre; ADL, acid detergent lignin; AIBP, agro-industrial by-product; ANF, antinutritional factor; BPH, by-product of pistachios hulling; BUN, blood urea nitrogen; CLA, conjugated linoleic acid; CP, crude protein; DM, dry matter; EE, ether extract; FA, fatty acid; FM, fresh matter; HU, hull; ME, metabolizable energy; NDF, neutral detergent fibre; OC, oil cake; OM, organic matter; PEG, polyethylene-glycol; PUFA;, polyunsaturated fatty acids; SK, skin; TAeq, tannic acid equivalents.

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Table 1
Chemical composition (g/kg DM) and nutritive value of nuts by-products [mean value ± standard deviation (number of studies)].

	Almond hulls[1–20]	Almond oil cake[21–23]	Almond skin[24,25]	Pistachio by-product[26–35]	Pistachio by-product silage[36–38]	Pistachio skin[39]	Hazelnut skin[40–47]	Hazelnut oil cake[48,49]	Walnut oil cake[50–53]	Walnut hulls[6,11]
DM, g/kg, as fed	897 ± 54 (12)	952 ± 8 (3)	899 (1)	922 ± 23 (9)	321 ± 14 (2)	952 (1)	919 ± 31 (3)	920 (1)	925 ± 22 (3)	951 ± 1 (2)
OM	884 ± 55 (6)	960 ± 18 (3)	952 (1)	806 ± 70 (5)	912 ± 44 (2)	na	na	na	939 ± 8 (2)	na
Ash	67 ± 29 (15)	40 ± 18 (3)	48 (1)	127 ± 23 (8)	88 ± 45 (2)	na	24 ± 1 (5)	60 (1)	61 ± 8 (2)	39 ± 35 (2)
CP	54 ± 16 (18)	350 ± 161 (3)	105 ± 2 (2)	126 ± 19 (10)	111 ± 27 (2)	218 (1)	84 ± 17 (6)	430 (1)	298 ± 111 (4)	38 ± 23 (2)
EE	24 ± 9 (11)	305 ± 241 (3)	228 ± 21 (2)	65 ± 14 (10)	80 ± 25 (2)	196 (1)	226 ± 1 (4)	30 (1)	165 ± 58 (3)	12 ± 2 (2)
NDF	420 ± 173 (11)	37 (1)	489 ± 53 (2)	277 ± 43 (9)	366 (1)	376 (1)	484 ± 72 (5)	308 (1)	413 (1)	638 ± 216 (2)
NDF ash-free	311 ± 58 (2)	na	na	331 ± 13 (2)	308 ± 36 (3)	na	na	na	na	na
ADF	287 ± 101 (14)	26 (1)	na	213 ± 45 (6)	261 (1)	157 (1)	385 ± 79 (5)	231 (1)	280 (1)	432 ± 266 (2)
ADF ash-free	214 ± 37 (2)	na	na	227 ± 28 (2)	218 ± 31 (3)	na	na	na	na	na
ADL	87 ± 33 (7)	7 (1)	na	77 ± 20 (3)	77 ± 28 (2)	26 (1)	199 ± 34 (5)	na	na	na
TP	87 ± 33 (2)	na	88 (1)	96 ± 20 (9)	139 ± 8 (2)	91 (1)	199 ± 93 (2)	0.125 (1)	na	38 (1)
TT	68 ± 42 (2)	na	na	56 ± 22 (9)	97 ± 6 (2)	44.1 (1)	118 ± 57 (2)	0.07 (1)	na	23 (1)
CT	na	na	na	6.7 ± 2.5 (2)	8.8 ± 3.7 (2)	na	40.2 ± 32.2 (2)	na	na	na
HT	na	na	na	39.0 ± 1.4 (2)	72.2 ± 24.3 (2)	na	141.1 (1)	na	na	na
ME[a] ruminant, MJ/kg	5.40 (1)	na	na	9.7 ± 2.3 (3)	8.4 (1)	na	13.2 (1)	na	na	na
ME[a] monogastric, MJ/kg	na	13.4 ± 1.6 (2)	na	na	na	na	na	9.8 (1)	14.1 ± 1.2 (2)	na

ADF, acid detergent fibre; ADL, acid detergent lignin; CP, crude protein; CT, condensed tannin; DM, dry matter; EE, ether extract; HT, hydrolysable tannin; ME, metabolizable energy; na, not analysed; NDF, neutral detergent fibre; OM, organic matter; TP, total phenol; TT, total tannin.
[1] Tor-Agbidye (1992); [2] Aguilar et al. (1984); [3] Alibés et al. (1983); [4] Calvert and Parker (1985); [5] Clutter and Rodiek (1992); [6] Delavar et al. (2013); [7] Elahi et al. (2017); [8] Getachew et al. (2004); [9] Hansen et al. (2020); [10] Homedes et al. (1993); [11] Kordi and Naserian (2020); [12] Rad et al. (2016); [13] Reed and Brown (1988); [14] Swanson et al. (2021); [15] Vonghia et al. (1989); [16] Wang et al. (2021b); [17] Wang et al. (2021c); [18] Williams et al. (2018); [19] Yalchi (2011); [20] Scerra et al. (2022); [21] Arjomandi et al. (2015); [22] Moradi Yeganeh et al. (2021); [23] Sol et al. (2017); [24] Mandalari et al. (2010); [25] Pasqualone et al. (2020); [26] Ghaffari et al. (2013); [27] Ghasemi et al. (2012a); [28] Ghasemi et al. (2012b); [29] Ghasemi et al. (2012c); [30] Sedighi-Vesagh et al. (2015); [31] Shakeri (2016); [32] Valizadeh et al. (2010); [33] Bakhshizadeh et al. (2014); [34] Mahdavi et al. (2010); [35] Razzaghi et al. (2015); [36] Babaei et al. (2015); [37] Rezaeenia et al. (2012); [38] Shakeri et al. (2014); [39] Naserian et al. (2015); [40] Caccamo et al. (2019); [41] Campione et al. (2020); [42] Candellone et al. (2019); [43] Daghio et al. (2021); [44] Marino et al. (2021); [45] Niderkorn et al. (2020); [46] Priolo et al. (2021); [47] Renna et al. (2020); [48] Erener et al. (2009); [49] Lammers et al. (2020); [50] Gheise et al. (2018); [51] Gheorghe et al. (2018); [52] Idriceanu et al. (2020); [53] Mir et al. (2017).

[a] Metabolizable energy was determined following different methods in each article [15–21–22–30–31–35–38–47–48–51–52].

activities are caused by agriculture, forestry, and other land use. Livestock is responsible for about 30% of greenhouse gas emissions from food production, due to enteric fermentation, manure and pasture management (Poore and Nemecek, 2018). According to Poore and Nemecek (2018), livestock emissions are related to others indirect emissions: crops for feed (6% of food emissions) and land use for livestock (16% of food emissions). To reduce environmental impact, livestock production must move toward a more sustainable system and a circular economy. The use of agro-industrial by-products (AIBPs) in replacement of feed crops is a strategy to reduce the environmental impact of feed production and transport, upcycle wastes, and limit the cost of their disposal (Kasapidou et al., 2015). Moreover, the replacement of human-edible feed crops with AIBPs can contribute to reduce the feed-food competition and address food security (Salami et al., 2019). By-products have always played an important role in animal nutrition, but their use is not exempt from weaknesses. For example, soybean meal is one of the most important protein feeds, but it is estimated that more than 80% of global production originates from 3 countries: Argentina, Brazil, and the USA (Kuepper and Stravens, 2022). In this context, the study of alternative AIBP gains importance to increase the resilience of livestock systems at local level.

The by-products of nuts industries have potential as alternative feed resources. In 2020, world nuts production was 5.3 million tonnes of kernels, with 80% from trees from temperate climate (International Nut Council, 2021). Considering that kernel represents about 50% of in-shell weight (Dufoo-Hurtado et al., 2021), about 5 million tonnes of nuts by-products are generated every year. Generally speaking, nuts by-products correspond to different parts of the nut: hulls (HU) and shells after hulling and shelling processes, skins (SK, also known as perisperm or testa) after blanching or roasting for confectionery industry, and oil cake (OC) after oil extraction (Dufoo-Hurtado et al., 2021). A relevant feature of nuts by-products is that they generally have a low moisture content. This is due to nuts being harvested when fruits dry out, or to specific industrial processes, as in the case of SKs obtained from nuts roasting. Nuts

Table 2
Mineral content, amino acids profile, and fatty acid profile of nuts by-products [mean value ± standard deviation (number of studies)].

Mineral content, g/kg dry matter	Almond hull[1–7]	Almond oil cake[8]	Pistachio skin[9]	Pistachio by-product[9–11]	Hazelnut oil cake[12–14]	Walnut oil cake[15]
Ca	3.47 ± 1.48 (6)	na	34.0 ± 9.9 (2)	8.8 (1)	34.0 ± 9.9 (2)	4.7 (1)
P	2.36 ± 2.89 (5)	82 (1)	78.5 ± 26.2 (2)	2.1 (1)	78.5 ± 26.2 (2)	0.66 (1)
K	30.1 ± 4.28 (5)	na	15.7 (1)	44.2 (1)	na	na
Na	0.15 ± 0.14 (5)	na	0.3 (1)	na	na	na
Mg	1.14 ± 1.36 (5)	na	1.9 (1)	3.1 (1)	na	na
Mn	0.014 ± 0.01 (5)	na	0.016 (1)	na	na	na
Fe	0.170 ± 0.04 (4)	na	0.016 (1)	na	na	na
Al	0.12 ± 0.08 (2)	na	na	na	na	na
Zn	0.01 ± 0.005 (4)	na	0.029 (1)	0.027 (1)	na	na
Cu	0.018 ± 0.026 (6)	na	0.015 (1)	0.016 (1)	na	na

Amino acid profile, g/kg dry matter	Almond hull[1–7]	Hazelnut oil cake[12–14]	*Fatty acid profile, g/100 g fatty acids*	Almond hull[1–7]	Pistachio by-product[9–11]	Pistachio skin[9]	Hazelnut skin[16–18]
Arginine	1.25 ± 0.07 (2)	45.3 (1)	C14:0	0.3 ± 0.4 (2)	1.47 (1)	0.2 (1)	0.05 ± 0.05 (3)
Lysine	1.45 ± 0.07 (2)	9.9 (1)	C16:0	15.8 ± 4.2 (2)	12.34 (1)	9.7 (1)	7.23 ± 1.10 (3)
Methionine	0.35 ± 0.07 (2)	1.5 (1)	C18:0	4.8 ± 2.2 (2)	2.22 (1)	1.3 (1)	3.51 ± 2.13 (3)
Threonine	1.2 ± 0.14 (2)	8.9 (1)	*cis*-9 C18:1	49.3 ± 5.7 (2)	47.8 (1)	45.1 (1)	74.00 ± 4.91 (3)
Valine	1.6 ± 0.14 (2)	12.6 (1)	*n*-6 C18:2	22.5 ± 5.2 (2)	26.94 (1)	42.8 (1)	12.28 ± 1.38 (3)
Leucine	1.85 ± 0.21 (2)	27.7 (1)	*n*-3 C18:3	4.0 ± 2.5 (2)	4.72 (1)	0.9 (1)	0.19 ± 0.03 (3)
Isoleucine	1.1 ± 0.14 (2)	28.2 (1)					
Histidine	0.7 ± 0 (2)	10.7 (1)					
Phenylalanine	1.25 ± 0.07 (2)	na					
Cystine	na	6.6 (1)					
Glycine	na	13.6 (1)					
Aspartic acid	na	45.7 (1)					
Proline	na	8.0 (1)					
Tyrosine	na	1.5 (1)					
Serine	na	15.8 (1)					
Glutamic acid	na	93.8 (1)					
Alanine	na	3.2 (1)					

na, not analysed.
[1] Wang et al. (2021b); [2] Wang et al. (2021c); [3] Swanson et al. (2022); [4] Alibés et al. (1983); [5] Williams et al. (2018); [6] Kilama et al. (2023); [7] Scerra et al. (2022); [8] Moradi Yeganeh et al. (2021); [9] Naserian et al. (2015); [10] Sedighi-Vesagh et al. (2015); [11] Razzaghi et al. (2015); [12] Erener et al. (2003); [13] Ozen and Erener (1992); [14] Yalçin et al. (2005); [15] Mir et al. (2015); [16] Caccamo et al. (2019); [17] Priolo et al. (2021); [18] Renna et al. (2020).

by-products are therefore easier to handle and store compared to other AIBPs, which generally contain high proportion of moisture. The main constraint on the dietary inclusion of nuts by-products is their content in phenolic compounds, an extremely heterogenous group of plant secondary compounds classified into different subgroups, such as phenolic acids, flavonoids, and tannins. Phenolic compounds can act as antinutritional factors (ANF) if a certain intake dose is exceeded (Vasta et al., 2019), especially in monogastric animals. However, animals can benefit from their bioactive properties with potential positive effects on animal health, while improving product quality (Biondi et al., 2019; Huang et al., 2018; Menci et al., 2021).

The aim of the present study is to review for the first time the existing scientific literature on the use of nuts by-products in livestock feeding, exploring the effects on nutrition, metabolism, performance, and product quality. This review focuses on the by-products obtained from the industrial processing of tree nuts from temperate climates: mainly almond, walnut, hazelnut, and pistachio, but also, although more briefly, chestnut and pine nut.

2. Methods

In the present article, the term "nut" is used in a general sense and not in a botanical sense. Google Scholar search engine was exploited to find scientific articles about the use of nuts by-products in livestock feeding. The primary keywords used for this search concerned 3 categories in combination: animal ("cow", "heifer", "bull", "steer", "calf", "sheep", "ewe", "lamb", "goat", "kid", "poultry", "broiler", "hen", "swine", "pig", "sow", "piglet", "rabbit", or "horse"), nut ("almond", "hazelnut", "pistachio", "walnut", "pine nut", or "chestnut"), and by-product ("cull", "skin", "perisperm", "oil cake", "meal", "hull", "shell", or "husk"). Other additional keywords were used to deepen the research, such as "meat quality", "dairy products quality", "digestibility", or "*in vitro*". The studies not written in English were discarded.

The search resulted in 84 studies selected for this review: almond (30 studies), pistachio (24), hazelnut (17), walnut (10), and pine nut (3). To the best of our knowledge, no studies are available on the use of chestnut by-products in animal nutrition. The nut species are discussed based on the relevance of their by-products to the livestock sector, considering the number of studies in the literature. Only the effects reported in the relevant studies with a significance of $P \leq 0.05$ are discussed in the text and displayed in the tables.

3. Nuts species and by-products

3.1. Almond

Almond (*Prunus dulcis* Mill.) is the most cultivated tree nut worldwide, with a production of 4.14 million tonnes of in-shell almonds in 2020 (FAOSTAT, 2022). The United States of America are the first producer of in-shell almonds followed by Spain (FAOSTAT, 2022). The main by-products generated during the industrial processing of almonds are almond HU, almond shells, almond SK, and almond OC (Garcia-Perez et al., 2021). The chemical composition of almond HU, SK, and OC is shown in Tables 1 and 2. Almond shells are not covered in this review as the high lignin content [300–380 g/kg dry matter (DM); Martínez et al. (1995)] makes them unsuitable for livestock feeding. As almond HU represents about 520 g/kg of the whole fruit (Prgomet et al., 2017), about 1 kg of this by-product is generated for 1 kg of in-shell almond, meaning an estimated world production of approximately 4 million tonnes. The chemical composition of almond HU is variable and depends on the almond variety (Homedes et al., 1993). In general, almond HU is rich in fibre, making them a suitable feedstuff for ruminants: for instance, almond HU is sometimes fed to dairy cows in California (Swanson et al., 2021). Almond SK represents 40 g/kg of the whole fruit, but contains most of the bioactive compounds of the whole almond (Esfahlan et al., 2010). These are mainly antioxidant molecules, such as tocopherols and phenolic compounds, useful for protecting the oil-rich kernel from oxidation (Chen et al., 2010). The bioactive compounds of almond SK have shown antiviral, anti-inflammatory, antiallergic, antimutagenic, anticarcinogenic, and anticholesterolemic properties (Chen et al., 2010). Indeed, research is currently focusing on extracting phenolic compounds, such as tannins, but also monounsaturated FA and polyunsaturated fatty acids (PUFA) from almond by-products (Chen et al., 2010; Esfahlan et al., 2010; Garcia-Perez et al., 2021). Almond OC is a by-product resulting from the extraction of almond oil, a valuable product used for cosmetics and pharmaceuticals purposes (Houmy et al., 2020). Considering an oil yield of about 33% (Rabadán et al., 2017), 770 g of almond OC is obtained from every kg of almond. Almond OC stands out from other almond by-products for its high content of crude protein, which can reach 480 g/kg of DM (Moradi Yeganeh et al., 2021).

3.2. Pistachio

Pistachio (*Pistacia vera* L.) is a plant characterised by a biennial bearing, which causes an important fluctuation in production. In the biennium 2019–2020, worldwide production of shell pistachio was on average 1.01 million tonnes (FAOSTAT, 2022). The three largest pistachio producers are Iran, USA, and Turkey (FAOSTAT, 2022). The pistachio fruit is a drupe that ripens in dense clusters, and twigs and leaves are often collected together with the fruits at harvesting. Thus, a considerable amount of by-product originates from pistachios hulling process, estimated at 1.5 kg of by-product for every kilo of pistachio in-shell (Bagheripour et al., 2008). The by-product of pistachio hulling (BPH) is composed of different parts of the fruit and the plant: external HU (645 g/kg), twigs (250 g/kg), leaves (100 g/kg), and fragments of kernel and shell (5 g/kg; Bagheripour et al., 2008). In Iran, woody shells are used as an energy source for domestic use whereas BPH is left to decompose in the field or occasionally fed to livestock, as recently studied by Alkhtib et al. (2017). This by-product can be dried to be stored longer, or ensiled to improve its palatability (Bagheripour et al., 2008; Shakeri et al., 2013). Pistachio SKs are characterised by a higher content of crude protein and lipids than other pistachio by-products. The chemical composition of pistachio by-products (Tables 1 and 2) is influenced by cultivar, period of harvesting, and conservation technique

(Alkhtib et al., 2017). Pistachio by-products contain many bioactive compounds, mainly phenolic compounds and tannins, which at high concentration may have antinutritional effects in livestock (Alkhtib et al., 2017; Bagheripour et al., 2008). For instance, the concentration [equivalents of tannic acid (TAeq) on DM basis] of phenolic compounds and tannins in the different plant organs are, respectively: 139 g/kg and 69 g/kg in leaves, 100 g/kg and 48 g/kg in twigs, 96 g/kg and 45 g/kg in HU (Alkhtib et al., 2017), and 91 g/kg and 44 g/kg in SKs (Naserian et al., 2015). Some methods, such as ensiling, drying, or adding polyethylene-glycol (PEG), are reported to deactivate tannins (Bagheripour et al., 2008). However, it cannot be ignored that dietary tannins can have positive effects on animal health, metabolism, livestock emissions, and product quality in both ruminants (Vasta et al., 2019; Frutos et al., 2020) and monogastric animals (Caprarulo et al., 2021; Huang et al., 2018).

3.3. Hazelnut

World hazelnut (*Corylus avellana* L.) production was 1.07 million tonnes of in-shell hazelnuts in 2020 (FAOSTAT, 2022). Turkey is the first producer, followed by Italy (International Nut Council, 2021). The by-products generated during harvesting and industrial processing are hazelnut shells, hazelnut SK, hazelnut OC, and cull hazelnuts. Considering the whole fruit, hazelnut shells and hazelnut SK represent around 500–550 g/kg and 20 g/kg of the total weight, respectively (Charron, 2019). Shells are rich in lignin (about 300 g/kg) and are currently used as a heating source (Pérez-Armada et al., 2019). The chemical composition of hazelnut SK and hazelnut OC (Tables 1 and 2) makes them suitable for animal feeding, the former being rich in lipids and the latter rich in proteins. In particular, hazelnut SK is rich in oleic acid, about 75 g/100 g fatty acids (FA; Renna et al., 2020), and has high antioxidant capacity thanks to the content of tocopherols and phenolic compounds (Priolo et al., 2021; Renna et al., 2020), which makes it interesting in animal nutrition.

3.4. Walnut

Walnuts (*Juglans regia* L.) are the second most produced nuts worldwide, with 3.32 million tonnes of in-shell product in 2020 (FAOSTAT, 2022). About 75% of global walnut production comes from four countries: China, USA, Iran, and Turkey (FAOSTAT, 2022). The walnut fruit is a pseudo-drupe with an external fleshy HU, the epicarp, and an inner hard shell, the endocarp, protecting the kernel. Three main by-products originate from harvest and industrial processes: walnut HU, walnut shells, and walnut OC. The chemical composition of walnut HU and walnut OC is reported in Tables 1 and 2. At harvest, walnut HU have an extremely low moisture content and are an interesting fibrous feedstuff. Regarding bioactive compounds, walnut HU is a mild source of phenols and tannins, with 38 and 23 g TAeq/kg respectively (Delavar et al., 2013). Both edible and non-edible walnut varieties are used for oil extraction, which has different purposes in cooking, medicine, cosmetics, or soap industry (Mir et al., 2017). Walnut OC represents about half the weight of the kernel before oil extraction (Mir et al., 2018), and its chemical composition varies according to the extraction technique (Martínez et al., 2008). The high content of lipids in walnut OC is remarkable (130 g/kg), especially for the richness in *n*-6 and *n*-3 PUFA (Mir et al., 2018). This makes walnut by-products prone to oxidation (Idriceanu et al., 2020), despite the presence of antioxidant molecules, such as γ-tocopherol (Maguire et al., 2004).

3.5. Pine nut

Pine nut is the seed of some plants of the genus *Pinus.* The calculation of global production is difficult because it mainly relies on natural forests, and significant annual variations occur (International Nut Council, 2021). In 2020/2021, the global pine nut production was about 38,000 tonnes of kernels, of which about 80% was obtained in Russia, China, and North Korea (International Nut Council, 2021). Harvesting and processing of pine nuts generate a considerable amount of by-products: for each tonne of kernels, more than two tonnes of shells and strobili are obtained and, often, discarded (Ivanova et al., 2019; Ivanov et al., 2020). This by-product has limited interest for animal nutrition given the high lignin content (450 g/kg). Recently, some authors tested the inclusion of pine nut shell flour in cow's diet at very low level (50 g/head/day), observing an improvement in milk yield, milk fat content, and curd quality (Ivanova et al., 2019; Tereshchenko et al., 2019; Ivanov et al., 2020). The authors attributed these positive effects to micronutrients and bioactive compounds present in pine nut shell, but without providing further details.

3.6. Chestnut

Chestnut is the fruit of *Castanea sativa* Miller and the total worldwide production was about 2.3 million tonnes in 2020, with China being the first producer, followed by Spain (FAOSTAT, 2022). The chestnut fruit is composed of a shell (pericarp) that protects the kernel, which is covered by a SK, and it is contained in a prickly bur. Burs are usually left on the forest floor after harvesting because they have no commercial purposes (Vázquez et al., 2010). Chestnut shells and SK are the main by-products of industrial processing, representing approximately 100 g/kg of the whole fruit (Echegaray et al., 2018). To our knowledge, there is currently no use for chestnut shells and SKs in animal nutrition. This fibrous by-product is interesting for its content in phenolic compounds, ranging from 27 to 52 g/kg (Morana et al., 2017).

4. Ruminants

4.1. Digestion and metabolism

Table 3 summarises the effects of nuts by-products in *in vitro* fermentation experiments. The effects of dietary nuts by-products on *in vivo* digestion and metabolism in ruminants are shown in Table 4.

4.1.1. Almond

Although almond HU have been traditionally used to feed ruminants (Elahi et al., 2017; Swanson et al., 2022), little information about its nutritional value and digestibility is available. Several variables influence almond HU digestibility: almond cultivar, growing condition, soil, agronomic practices, climate condition, etc. For example, OM digestibility and metabolizable energy (ME) of almond HU range between 38% and 65% and 5.7 and 9.5 MJ/kg of DM respectively, according to different *in vitro* studies (Getachew et al., 2004; Delavar et al., 2013). Another factor to consider is the moisture content of almond HU. Elahi et al. (2017) showed a higher *in vitro* gas production for dry than for fresh almond HU, suggesting a higher digestibility of dry almond HU. However, Swanson et al. (2022) remarked that the analyses performed by Elahi et al. (2017) on dry and fresh almond HU did not reflect reality. Indeed, modern harvesting and hulling technologies do not allow the complete elimination of debris, such as twigs or ground dirt, and so to have a pure HU. As would be expected, the *in vitro* gas production and digestibility of almond HU decrease in the presence of debris (270 *vs* 261 ml/g) because of the high content of fibre, lignin, and ash, which reduce the proportion of easily digestible compounds (Swanson et al., 2021). Finally, in contrast to other results (Elahi et al., 2015; Swanson et al., 2022), Williams et al. (2018) showed that *in vitro* methane production decreased by 16% when mixing 1:1 almond HU with a control concentrate (barley, oats, wheat, straw, and lupins), without affecting *in vitro* gas production. Probably, this was due to the inhibition of methanogen microbiota by the tannins (Jayanegara et al., 2013) and/or the triterpenoids (Takeoka et al., 2000) contained in almond HU.

Concerning *in vivo* experiments, the replacement of alfalfa hay with 300 g/kg of almond HU reduced the digestibility of NDF (−19%) and CP (−22%) in sheep (Yalchi, 2011). This effect could be attributed to the low CP content of almond HU, which caused a suppression of rumen bacterial activity. Indeed, different results were obtained when diets were supplemented with a N source in order to be isonitrogenous. The inclusion of almond HU in the diet of lambs (Alibés et al., 1983; Rad et al., 2016), cows (Swanson et al., 2021), and steers (Aguilar et al., 1984) had no adverse effects on digestion when the CP loss was balanced by adding urea or soybean meal. Also, feeding 200 g/kg of almond HU to dairy cows, together with a small supplement of 22 g/kg soybean meal, improved the digestibility of DM, ADF, and CP (+8%, +13%, and +6%, respectively; Swanson et al., 2021). This latter result could be due to the effect of almond HU inclusion on eating behaviour. In fact, when replacing part of the concentrates with almond HU, Swanson et al. (2021) observed an increase in eating and rumination times, which probably enhanced the digestion of the diet. The inclusion of

Table 3
Effects of nuts by-products on *in vitro* rumen digestion.

By-product	Dose (g/kg DM)	Effect[a]	Reference
Almond			
Almond hulls	1000	Higher GP than peanut hulls and walnut hulls.	Kordi and Naserian (2020)
Almond hulls	1000	Higher GP, OM digestibility, and ME than walnut hulls.	Delavar et al. (2013)
Almond hulls	1000	Lower digestibility than corn grain and soybean meal.	Getachew et al. (2004)
Almond hulls	125–250–500	Lower CH_4 production with 500 g/kg.	Williams et al. (2018)
Almond hulls, green or dry	1000	Higher GP and DM digestibility with dry hulls than green hulls.	Elahi et al. (2017)
Almond hulls, with or without debris	1000	Lower GP and DM digestibility in presence of debris.	Swanson et al. (2022)
Pistachio			
BPH, silage or airdried, with or without PEG	1000	Lower tannin and fibre contents in silage. Lower digestibility with silage. Higher digestibility with PEG.	Bagheripour et al. (2008)
BPH, silage	20–40–60–80–100	Linear reduction in GP, OM digestibility, ME, and CH_4.	Denek et al. (2017)
BPH, with or without PEG	1000	Higher GP, ME, and OM digestibility with PEG.	Bakhshizadeh et al. (2014)
BPH	1000	Adaptation of rumen microbiota, with bacteria closely related to *Streptococcus gallolyticus, S. waius,* and *S. bovis.*	Babaei et al. (2015)
Hazelnut			
Hazelnut skin	82	Lower GP, DM digestibility, and NH_3 and CH_4 productions.	Niderkorn et al. (2020)
Walnut			
Walnut hulls	1000	Lower GP than almond hulls.	Kordi and Naserian (2020)
Walnut hulls	1000	Lower GP, OM digestibility, and ME than almond hulls.	Delavar et al. (2013)
Walnut hulls	100–150–200–250–300	Lower DM digestibility, OM digestibility, and microbial biomass production with doses $\geq$ 150 g/kg.	Mir et al. (2015)

BPH, by-product of pistachio hulling; DM, dry matter; GP, gas production; ME, metabolizable energy; OM, organic matter; PEG, polyethylene glycol.
[a] In comparison with the control treatment. Only the effects with P $\leq$ 0.05 were reported.

Table 4
Effect of feeding nuts by-products to ruminants on *in vivo* digestion and metabolism.

By-product	Animal	Dose (g/kg DM)	Effect[a]	Reference
Almond				
Almond hulls	Steer	200–400	None.	Aguilar et al. (1984)
Almond hulls, urea treated	Lamb	200–400	None.	Rad et al. (2016)
Almond hulls, ground or coarse		*ad libitum*	Lower OM and fibre digestibility with coarse than with ground.	Alibés et al. (1983)
Almond hulls, low-N or high-N		*ad libitum*	Lower feed intake in low-N diet than in high-N diet.	
Almond hulls	Sheep	300	Lower NDF and CP digestibility.	Yalchi (2011)
Almond hulls	Cow	70–130–200	Higher DM, OM, ADF, and CP digestibility.	Swanson et al. (2021)
Almond hulls		180	None.	Williams et al. (2018)
Almond hulls	Goat	150–250–350	Lower DM, OM, and NDF intake with doses ≥ 250 g/kg.	Reed and Brown (1988)
Almond hulls		200–400	Lower BUN.	Can et al. (2007)
Pistachio				
BPH	Calf	60–120–180	Lower BUN with 60 g/kg.	Shakeri et al. (2013)
BPH, silage		60–120–180	Lower VFA production and higher rumen pH with doses > 120 g/kg.	Shakeri et al. (2014)
BPH	Lamb	100–200–300	Lower NDF digestibility with 200 g/kg. Lower CP digestibility and BUN with 300 g/kg.	Shakeri (2016)
BPH		100–200–300	None.	Valizadeh et al. (2010)
BPH	Sheep	120–240–360	Lower BUN. Lower VFA production with 360 g/kg.	Ghaffari et al. (2013)
BPH		200–400	Lower VFA production and higher rumen pH. Higher lipid and protein digestibility with 400 g/kg.	Ghasemi et al. (2012a)
BPH		200–400	Modification of rumen microbiota: lower relative abundance of *Fibrobacter succinogenes* and *Ruminococcus albus*.	Ghasemi et al. (2012b); c
BPH, silage	Cow	50–100–150	None.	Rezaeenia et al. (2012)
BPH, silage		150	None.	Mokhtarpour et al. (2012)
BPH	Goat	240	Lower VFA production and BUN.	Razzaghi et al. (2015)
Pistachio skin		70–140–210	Higher cholesterol and triglycerides contents in serum. Higher protein digestibility with 210 g/kg.	Naserian et al. (2015)
BPH		320	Lower protein digestibility. Higher BUN and aspartate aminotransferase in serum.	Sedighi-Vesagh et al. (2015)
Hazelnut				
Hazelnut skin	Lamb	150	Lower relative abundance of microbial genera correlated to C18:1 *trans*10 production.	Daghio et al. (2021)
Hazelnut skin		150	Lower valerate production and higher butyrate production.	Priolo et al. (2021)
Walnut				
Walnut oil cake	Goat	100	None.	Mir et al. (2017)
Walnut oil cake		100	Higher aspartate aminotransferase in serum.	Mir et al. (2018)
Walnut oil cake	Cow	94.5	None.	Gheise et al. (2018)

ADF, acid detergent fibre; BPH, by-product of pistachio hulling; BUN, blood urea nitrogen; CP, crude protein; DM, dry matter; NDF, neutral detergent fibre; OM, organic matter; VFA, volatile fatty acid.

[a] In comparison with the control treatment. Only the effects with P ≤ 0.05 were reported.

almond HU up to 400 g/kg DM in lambs (Rad et al., 2016) and 180 g/kg in dairy cow (Williams et al., 2018) did not result in any detrimental effects on volatile FA production and rumen protozoa population. Concerning methane production, the positive results obtained in *in vitro* tests were not confirmed by an *in vivo* trial with dairy cows (Williams et al., 2018), but further research on this aspect is needed. In addition, feeding goats up to 400 g/kg of almond HU reduced blood urea nitrogen (BUN), indicating an improved N metabolism (Can et al., 2007). This effect could be due to the tannin content of almond HU, as tannins are proven to reduce ruminal ammonia, BUN, and urinary N excretion (Herremans et al., 2020).

4.1.2. Pistachio

As previously reported, BPH is a heterogeneous mixture of HU, twigs, leaves, and fragments of kernel and shell, therefore difficult to standardise. The main limit of using pistachio by-products as feedstuff is related to their high content of phenolic compounds, that may have detrimental effect on digestion (Alkhtib et al., 2017). When corn silage was mixed with up to 100 g/kg of BPH, lower *in vitro* gas production, OM digestibility, and ME were observed (Denek et al., 2017). Ensiling or adding PEG may contrast the effects of tannins (Bagheripour et al., 2008). However, ensiling BPH led to degradation of substrates (*e.g.*, starch and fibre) useful for ruminal microbial growth, worsening the overall *in vitro* digestibility (0.46 *vs* 0.49 g/kg DM; Bagheripour et al., 2008). Instead, the addition of PEG to BPH had a positive influence on digestibility by establishing a deactivating bond with tannins, resulting in improved *in vitro* gas production (+19%) and OM digestibility (+15%; Bagheripour et al., 2008; Bakhshizadeh et al., 2014). On the other hand, the presence of tannin may have positive effects. The inclusion of 100 g/kg of BPH reduced by 43% the *in vitro* methane production, with a lower methane proportion on total *in vitro* gas production (Denek et al., 2017). This effect was likely due to the specific effect of tannins against methanogens (Vasta et al., 2019). Although tannins interfere with rumen microbiota in the short term, microbiota composition can adapt to a tannin-rich diet in the long term. Bacteria families resistant to tannins were more abundant in rumen fluid of sheep adapted to consume tannin-containing diet compared to a rumen fluid from sheep fed with conventional feedstuff (Babaei et al., 2015). These bacteria families, closely related to *Streptococcus gallolyticus, S. waius,* and *S. bovis.*, developed a tannin resistance strategy, such as the ability to degrade some hydrolysable tannins using alternative enzymes. Consequently, they were able to use tannins-rich feed as substrates, increasing the *in vitro* digestibility of BPH compared to sheep fed conventional feedstuff (Babaei et al., 2015). Basing on *in vitro* studies, a concentration of up to 100 g of BPH/kg in the diet of lambs could be a good compromise between diet digestibility and the reduction of pollutant emissions.

Feeding animals a diet including BPH reduced the volatile FA production in sheep (−3%, Ghaffari et al., 2013; −24%, Ghasemi et al., 2012a), goat (−10%, Razzaghi et al., 2015), and calves (−10%, Shakeri et al., 2014). Concerning rumen pH, most of the *in vivo* studies reported no effect of dietary BPH (Rezaeenia et al., 2012; Mokhtarpour et al., 2012; Ghaffari et al., 2013; Shakeri et al., 2014; Razzaghi et al., 2015), whereas others reported an increase (Ghasemi et al., 2012a; Naserian et al., 2015). In line with this, contrasting effects have been reported on the *in vivo* digestibility of nutrients, such as NDF, proteins, and lipids. Feeding BPH reduced protein and NDF digestibility in lambs (Shakeri, 2016), and protein digestibility in dairy goats (Sedighi-Vesagh et al., 2015). As for *in vitro* studies, the reduction in *in vivo* nutrients digestibility is likely due to the presence of tannins, able to reduce the activity of rumen microorganisms. Ensiling BPH has proven to effectively improve its nutritional quality and remove the negative effects on *in vivo* digestibility (Shakeri et al., 2014; Rezaeenia et al., 2012; Mokhtarpour et al., 2012).

However, opposite results were observed in sheep, as feeding 400 g/kg of BPH increased the digestibility of protein (0.76 *vs* 0.65 g/g) and lipids (0.79 *vs* 0.60 g/g; Ghasemi et al., 2012a). Similarly, feeding 210 g/kg of pistachio SK to dairy goats increased by 6% the digestibility of protein (Naserian et al., 2015). Indeed, low to moderate concentrations of tannins in the diet may have beneficial effects, such as the protection of dietary protein against ruminal degradation (Frutos et al., 2004). Furthermore, changes in the ruminal environment caused by tannin intake can modify the composition of the rumen microbiota. The DNA analyses of rumen fluid from sheep fed with 200 g/kg of BPH showed a lower presence of some cellulolytic bacteria, such as *Fibrobacter succinogenes* and *Ruminococcus albus* (Ghasemi et al., 2012b; c). On the contrary, Ghaffari et al. (2013) did not report any alteration of sheep rumen microbiota when feeding up to 360 g/kg of BPH.

Concerning blood biochemical parameters, *i.e.,* glucose, total cholesterol, insulin, and triglycerides, no negative effect of dietary BPH was observed in lambs (Valizadeh et al., 2010; Shakeri, 2016), sheep (Ghaffari et al., 2013; Ghasemi et al., 2012a), goats (Sedighi-Vesagh et al., 2015), calves (Shakeri et al., 2013), and cows (Mokhtarpour et al., 2012; Rezaeenia et al., 2012). The only parameter reported to be affected is BUN, which fell as the BPH dose increased (Ghaffari et al., 2013; Mokhtarpour et al., 2012; Shakeri et al., 2013; Sedighi-Vesagh et al., 2015; Razzaghi et al., 2015; Shakeri, 2016). The variation of BUN could be due to the lower ruminal degradation and intestinal absorption of protein, likely related to the tannins present in pistachio by-product (Herremans et al., 2020). Interestingly, the inclusion of 320 g/kg of BPH in the diet caused an increase in the blood alanine aminotransferase value in dairy goats (Sedighi-Vesagh et al., 2015). This was attributed to liver damage due to ANF such as phenolic compounds (Kohl et al., 2015). Generally, pistachio by-products can be used as a partial replacement of forage without negative effects on digestion, although excessive doses can lead to deleterious effects due to the presence of tannins or other ANF.

4.1.3. Hazelnut

Among hazelnut by-products, only SK was studied for its effects on ruminant metabolism and digestion. Adding 82 g/kg DM hazelnut SK to a commercial basal diet reduced by 7% *in vitro* gas production, especially methane, while pH and volatile FA were not influenced (Niderkorn et al., 2020). The decrease in *in vitro* DM digestibility suggested an influence of the tannins contained in hazelnut pericarp (63 g TAeq/kg DM). These phenolic compounds also reduced the protein degradation (−33%), and this could lead to a better efficiency of N utilisation (Niderkorn et al., 2020). Concerning *in vivo* studies, feeding lambs with 150 g/kg of hazelnut SK did not affect total volatile FA production (Priolo et al., 2021). However, the proportion of volatile FA changed, by increasing butyrate (+39%) and reducing valerate (−98%), and rumen biohydrogenation was modulated (Priolo et al., 2021). This effect was probably due to the high content in tannins and C18:1 *c*9 of hazelnut SK, which affected the activity and the equilibrium of rumen microbiota. In particular, the presence of the bacterial genus *Dialister* decreased in lambs fed with 150 g/kg of hazelnut SK (Daghio et al., 2021). This genus represented 7.66% of bacterial community in lambs fed conventional diet and moved to 1.48% in lambs fed hazelnut SK. Interestingly, *Dialister* genus is positively correlated with C18:1 *t*10 (Daghio et al., 2021), a FA that might be detrimental for animal performance and perhaps human health (Alves et al., 2021).

4.1.4. Walnut

The walnut by-products that have been studied for *in vitro* digestion were walnut OC (Mir et al., 2015) and walnut HU (Delavar et al., 2013; Kordi and Naserian, 2020). At low inclusion levels, walnut OC did not affect the *in vitro* digestibility of a commercial concentrate (Mir et al., 2015). However, adding 150 g/kg or more walnut OC led to a reduction in *in vitro* DM digestibility, OM digestibility, and microbial biomass production (−13%, −16%, and −26%, respectively; Mir et al., 2015). These differences could be related to the high content of lipids in walnut OC. Walnut lipids are largely composed of PUFA (Maguire et al., 2004), which could have detrimental effects on rumen microbial activity when used at high doses. The *in vitro* fermentation of walnut HU showed contrasting results. In particular, OM digestibility was 51.6% *vs* 19.2%, and ME was 7.8 MJ/kg DM *vs* 2.7 MJ/kg DM, in the studies of Delavar et al. (2013) and Kordi and Naserian (2020), respectively. These evident differences could be due to the nutritional composition of the HU. The walnut HU tested by Kordi and Naserian (2020) were richer in NDF (+30.5%) and ADF (+37.6%) than those tested by Delavar et al. (2013), but poorer in crude protein (−3.1%) and ether extract (−4.4% DM). The great variability in chemical composition between by-products batches is one of the most limiting factors related to the use of AIBPs in animal nutrition.

Walnut OC is the most studied walnut by-product in *in vivo* ruminant feeding. Feeding walnut OC did not result in any deleterious effects on feed intake and nutrient digestibility in goats, up to 100 g/kg (Mir et al., 2017, 2018), and in cows, up to 94.5 g/kg (Gheise et al., 2018). Similarly, N balance in cows (Gheise et al., 2018), and calcium and phosphorus balance in goats (Mir et al., 2018) were not affected by dietary walnut OC. Mir et al. (2018) suggested that the tannins contained in walnut OC could be toxic for liver, as they found high level of aspartate aminotransferase, a biomarker usually associated to liver damage. However, according to the values of goat's blood parameters from other studies (Djuricic et al., 2011; Rumosa Gwase et al., 2012), the value of aspartate aminotransferase in goats fed walnut OC from the experiment of Mir et al. (2018) fell within a normal range (between 167 and 513 U/l). Overall, walnut OC can be fed to ruminants without deleterious effects, although the effects on aspartate aminotransferase should be further explored.

4.2. Growth performance and meat quality

Only a few studies have tested the effects of feeding ruminants with nuts by-products on growth performance and product quality in meat-oriented farming systems. The main results of these studies, mostly on lambs, are summarised in Table 5.

4.2.1. Almond

The effects of almond HU as alternative feedstuff on growth performance were studied only on lambs. Lambs fed up to 400 g/kg almond HU consistently showed the same growth rate and carcass characteristics compared to lambs fed with conventional diet (Rad et al., 2016; Vonghia et al., 1989; Phillips et al., 2015; Scerra et al., 2022). Feeding lambs with 150 or 300 g/kg almond HU for 40 days before slaughtering increased the oxidative stability of raw and cooked meat (Scerra et al., 2022). In particular, the malondialdehyde content was more than halved in the meat of the almond HU-fed lambs compared with the control group This was probably due to the presence of antioxidants, such as flavonoids, terpenoids, and phenolic compounds, in almond HU (Scerra et al., 2022).

4.2.2. Pistachio

Feeding pistachio by-products to ruminants resulted in contrasting effects on growth performance, likely due to the huge variability in terms of nutritional value and, in particular, tannin content. Generally, a medium-low dose of about 150 g/kg of BPH can be administered to calves without detrimental effects (Shakeri et al., 2013). Even, some studies did not observe any detrimental effects with a diet concentration of up to 300 g/kg of BPH in lambs (Valizadeh et al., 2010; Norouzian and Ghiasi, 2012). The authors suggested that the tannin-rich feed was palatable when fed as mixed ration (Valizadeh et al., 2010) or that the type of tannin did not have an astringent taste that would reduce the intake (Norouzian and Ghiasi, 2012). Quite the opposite, a dose of BPH higher than 150 g/kg negatively affected the growth performance of lambs, decreasing final body weight by 24% and 7%, according to the results of Shakeri (2016) and Mahdavi et al. (2010) respectively. It is well known that tannins react with taste receptors, causing an astringent sensation and, consequently, when fed at high doses, a reduction in intake and growth performance (Shakeri, 2016; Ghasemi et al., 2012a). However, a well-planned diet management could benefit from exploiting the synergy of different by-products. For example,

Table 5
Effect of feeding tree nuts by-products to ruminants on growth performance and meat quality.

By-product	Animal	Dose (g/kg DM)	Effect[a]	Reference
Almond				
Almond hulls, urea treated	Lamb	200–400	None.	Rad et al. (2016)
Almond hulls		150–300	None.	Vonghia et al. (1989)
Almond hulls		50–100	None.	Phillips et al. (2015)
Almond hulls		150–300	Higher oxidative stability in raw and cooked meat	Scerra et al. (2022)
Pistachio				
BPH	Calf	60–120–180	Higher ADG with 60 g/kg.	Shakeri et al. (2013)
BPH	Lamb	100–200–300	None.	Norouzian and Ghiasi (2012)
BPH		100–200–300	Lower final body weight with 300 g/kg.	Shakeri (2016)
BPH		100–200–300	None.	Valizadeh et al. (2010)
BPH, with date by-product		70–140–210	Higher growth performance and final body weight.	SoltaniNezhad et al. (2016)
Pistachio hulls		100–150–200–250–300–350	Lower final body weight with doses ≥ 150 g/kg.	Mahdavi et al. (2010)
Hazelnut				
Hazelnut skin	Lamb	150	Lower FCR increasing feed intake. Higher PUFA and C18:1 *trans*11 in intramuscular fat.	Priolo et al. (2021)
Hazelnut skin		150	Higher α-tocopherol content in muscle. Lower lipid oxidation in fresh meat over 7 d of storage.	Menci et al. (2023)
Hazelnut skin		150	Higher protein degradation in meat during storage.	Della Malva et al. (2023a)
Hazelnut skin		150	Different proteome in meat.	Della Malva et al. (2023b)
Hazelnut oil cake		108	Higher ADG.	Sariçiçek (2000)

ADG, average daily gain; BPH, by-product of pistachio hulling; FCR, feed conversion ratio; PUFA, polyunsaturated fatty acid.
[a] In comparison with the control treatment. Only the effects with P ≤ 0.05 were reported.

SoltaniNezhad et al. (2016) reported a 1.4 kg increase in final body weight of lambs fed with 210 g/kg of a mixture of BPH silage and dates waste. According to the authors, ensiling BPH reduced its tannin content while dates waste provided sugar to the diet, resulting in an overall good palatability and nutritive value. In particular, the higher final body weight was related to an improvement in carcass characteristic, fatness, and organs size (SoltaniNezhad et al., 2016).

4.2.3. Hazelnut

Lambs fed with 150 g/kg of hazelnut SK in replacement of corn showed the same DM intake, average daily gain, and final body weight compared to lambs fed with a conventional diet (Priolo et al., 2021). However, feed conversion ratio was higher, so lambs fed hazelnut SK would need more feed for growing, probably because of the greater concentration of indigestible protein in the diet (Priolo et al., 2021). Concerning meat quality, including hazelnut SK in lambs' diet enriched the intramuscular fat in PUFAs and vaccenic acid, which are known to have health-promoting effects (Priolo et al., 2021). This is likely related to the modulation of rumen biohydrogenation by the high concentration of tannins and C18:1 *c*9 in hazelnut SK. Moreover, the meat from lambs fed hazelnut SK had twice as much α-tocopherol content compared to the control group (Menci et al., 2023). This was likely due to the transfer of tocopherols from hazelnut SK (about 161 mg/kg DM) to muscle. Due to the antioxidant activity of α-tocopherol, the lipid oxidation in fresh meat over 7 days of refrigerated storage was reduced (0.6 *vs* 1.7 mg/kg of malondialdehyde; Menci et al., 2023). Hazelnut OC was studied as a protein source in lambs' diet, in comparison with urea, soybean meal, and corn gluten meal (Sariçiçek, 2000). In this case, hazelnut OC increased average daily gain but did not influence final body weight. This difference could be attributable to the type of protein, which is more resistant to rumen degradation and more adsorbable in the intestine.

4.3. Milk production and quality of dairy products

Nuts industries by-products were mainly tested on dairy cows, and secondarily on goats and sheep. The results of these studies are summarised in Table 6. To the best of our knowledge, no study investigated the effect of feeding walnut by-products on milk production and dairy products.

4.3.1. Almond

Although almond by-products find their practical application in the diet of dairy ruminants, mainly at the local level (Swanson et al., 2021), only few studies have focused on this topic. In general, almond HU can be included in the diet of dairy cows as a partial substitute for alfalfa (Aguilar et al., 1984; Williams et al., 2018) or concentrates (Swanson et al., 2021) without negatively affecting

Table 6
Effects of feeding nuts by-products to ruminants on milk production and dairy products quality.

By-product	Animal	Dose (g/kg DM)	Effect[a]	Reference
Almond				
Almond hulls	Cow	70–130–200	Lower milk protein and fat contents, and protein yield.	Swanson et al. (2021)
Almond hulls		125–250	None.	Aguilar et al. (1984)
Almond hulls		180	Lower milk and protein yields. Lower PUFA proportion in milk.	Williams et al. (2018)
Almond hulls	Goat	150–250–350	Lower milk protein content with 350 g/kg.	Reed and Brown (1988)
Pistachio				
BPH, silage	Cow	50–100–150	None.	Rezaeenia et al. (2012)
BPH, silage		150	None.	Mokhtarpour et al. (2012)
BPH	Goat	240	Higher milk protein content.	Razzaghi et al. (2015)
BPH		320	Lower SFA proportion and higher UFA proportion in milk.	Sedighi-Vesagh et al. (2015)
Pistachio skin		70–140–210	Higher milk fat content.	Naserian et al. (2015)
Hazelnut				
Hazelnut oil cake	Cow	188	Higher milk fat content.	Sariçiçek (2000)
Hazelnut skin		1 kg/head/day	Modification of milk FA profile: higher C18:1 *cis*9, C18:1 *trans*11, CLA, total *trans*-FA, and *n*-6/*n*-3 PUFA; lower C18:0 and OBCFA. Higher tocopherols content in milk.	Renna et al. (2020)
Hazelnut skin	Ewe	360	Lower milk protein content. Modification of milk FA profile: higher C18:1 *cis*9, C18:1 *trans*11, and CLA; lower C18:3 *n*-3 and atherogenic index.	Campione et al. (2020)
Hazelnut skin		360	Higher cheese fat content. Modification of cheese FA profile: higher C18:1 *cis*9, C18:1 *trans*11, and C18:2 *cis*9*trans*11; lower C14:0 and C16:0. Lower cholesterol content in cheese. Higher tocopherols content.	Marino et al. (2021)
Hazelnut skin		360	Higher cheese off-flavours (spicy and acid attributes).	Caccamo et al. (2019)

BPH, by-product of pistachio hulling; CLA conjugated linoleic acid; FA, fatty acids; MUFA mono-unsaturated fatty acid; OBCFA, odd- and branched-chain fatty acids; PUFA polyunsaturated fatty acid; SFA saturated fatty acid; UFA unsaturated fatty acid.

[a] In comparison with the control treatment. Only the effects with $P \leq 0.05$ were reported.

milk production. Nevertheless, nitrogen supplementation may be necessary to avoid deficiencies that can affect milk protein yield. Aguilar et al. (1984) reported no negative effect on milk yield and composition after feeding dairy cows 250 g/kg of almond HU with urea supplementation. On the contrary, Williams et al. (2018) found a 10% reduction in the protein yield of dairy cows fed 180 g/kg of almond HU, probably due to the lower CP content in the almond HU diet than in the control one. Recently, Swanson et al. (2021) observed that diets containing 70 g/kg of almond HU as a partial substitute for corn and soy can be successfully fed to dairy cows. However, when the concentrates were further reduced and almond HU reached 200 g/kg in the diet, milk protein content decreased and milk fat content increased (Swanson et al., 2021). This could be due to the replacement of concentrates with a fibre source such as almond HU, which may have increased acetate and butyrate productions, leading to higher milk fat production. Concerning small ruminants, almond HU can be fed to dairy goats in replacement of alfalfa (up to 350 g/kg) without detrimental effects on milk

Table 7
Effects of feeding nuts by-products to monogastric animals on digestion, metabolism, growth performance, and product quality.

By-product	Animal	Dose (g/kg DM)	Effect[a]	Reference
	Poultry			
Almond				
Almond oil cake	Broilers	70–140–210–280	Lower final body weight, and higher weight of gastrointestinal tract. Lower cholesterol, triglycerides and LDL, and higher HDL and glucose in serum.	Moradi Yeganeh et al. (2021)
Almond hulls		25–50–75–100	Lower fatness with 50 g/kg.	Wang et al. (2021a)
Almond hulls		30–60–90	Lower DM digestibility.	Wang et al. (2021b)
Almond hulls	Laying hens	75–150	Higher N digestibility. Higher yolk colour intensity. Lower final body weight and fatness with 75 g/kg.	Wang et al. (2021c)
Almond oil cake	Quails	100–200–300	Lower LDL, cholesterol, and uric acid in serum.	Arjomandi et al. (2015)
Hazelnut				
Hazelnut oil cake	Broilers	50%– 100% of protein	Lower final body weight and fatness. Higher weight of gizzard and edible organs.	Erener et al. (2009)
Hazelnut oil cake	Laying hens	34–68–102–136–171	None.	Ozen and Erener (1992)
Hazelnut oil cake	Quails	98–195–293–391	Lower growth rate in first few weeks, but similar final body weight.	Erener et al. (2003)
Hazelnut oil cake		78–156–235–313	Higher yolk weight. Maximum egg productivity and egg weight with 156 g/kg.	Erener et al. (2003)
Hazelnut oil cake		100–150–200–250–300	None.	Yalçin et al. (2005)
Walnut				
Walnut oil cake	Quails	100–200–300	Lower LDL, cholesterol, and triglycerides in blood serum.	Arjomandi and Salarmoini (2016)
	Swine			
Almond				
Almond hulls		150	Lower feed intake, digestibility, and carcass fatness.	Homedes et al. (1993)
Almond hulls		50–100–150	None.	Calvert and Parker (1985)
Residues and broken almonds		20–40–70–100	Lower OM and gross energy digestibility.	Sol et al. (2016)
Hazelnut				
Cull hazelnut		100	Modification of meat FA profile: lower SFA and C16:0; higher MUFA and C18:1 *cis*9.	Lammers et al. (2020)
Walnut				
WOC and linseed (3:5)		80	Lower muscle pH. Higher values of lightness (L*) and redness (a*) in meat.	Idriceanu et al. (2020)
WOC and linseed (1:1)		250	Lower proteins and uric acid in serum.	Târnoveanu et al. (2019)
WOC and linseed (1:8)	Piglets	90	Higher ADG and final body weight. Higher BUN.	Gheorghe et al. (2018)
	Rabbits			
Almond				
Almond hulls		200–400–600	Lower final body weight with 600 g/kg.	Tor-Agbidye (1992)
Hazelnut				
Hazelnut skin and linseed (3:10)		65	Lower values of oxidative stress markers in serum.	Candellone et al. (2019)
	Horses			
Almond				
Almond hulls		400	Longer glucose and insulin response over time.	Hansen et al. (2020)
Almond hulls		150–300–450	Higher DM and gross energy digestibility. Lower protein digestibility.	Clutter and Rodiek (1992)

ADG, average daily gain; BUN, bloody urea nitrogen; DM, dry matter; HDL, high-density lipoprotein; LDL, low-density lipoprotein; MUFA, monounsaturated fatty acid; OM, organic matter; SFA, saturated fatty acid; WOC, walnut oil cake.

[a] In comparison with the control treatment. Only the effects with $P \leq 0.05$ were reported.

production and composition (Reed and Brown, 1988).

4.3.2. Pistachio

Pistachio by-products have been successfully fed to dairy cows and goats. Regarding dairy cows, BPH silage was used as a substitute for corn silage in the diet (up to 150 g/kg): no differences were observed in milk yield and composition compared to milk from cows fed a conventional diet (Mokhtarpour et al., 2012; Rezaeenia et al., 2012). In goat diet, the replacement of wheat bran with 240 g/kg of BPH increased milk protein content by about 7%, although BPH and wheat bran had a similar nutritional composition (Razzaghi et al., 2015). Conversely, feeding 320 g/kg of BPH in place of alfalfa hay did not influence milk yield and composition in dairy goats (Sedighi-Vesagh et al., 2015). However, milk FA profile showed a reduction in total saturated FA and an increase in monounsaturated FAs, PUFAs, conjugated linoleic acid (CLA), C18:1 *t*11, and C18:1 *c*9 (Sedighi-Vesagh et al., 2015). This could be due to the higher proportion of unsaturated FAs and tannins in BPH than in alfalfa hay, which modified ruminal biohydrogenation and/or reduced *de novo* synthesis of short FAs in the mammary gland (Chilliard and Ferlay, 2004). This could have implications for the enrichment of ruminant milk in desirable FAs, such as CLA, C18:1 *t*11, and unsaturated FAs, which are known to have potential positive effects on human health (Chilliard et al., 2007). Finally, the inclusion of pistachio SK in goats' diet up to a concentration of 210 g/kg in place of wheat bran quadratically increased milk fat content (Naserian et al., 2015). For instance, milk fat content was 3.10% in the goats fed control diet and 3.96% in the goat fed with 140 g/kg of pistachio SKs. This effect was attributable to the higher energy level of pistachio SK, compared to wheat bran, and to the increase in DM intake due to the palatability of pistachio SK.

4.3.3. Hazelnut

Two hazelnut by-products have been used as feed for dairy ruminants: hazelnut OC (Sariçiçek, 2000) and, recently, hazelnut SK (Caccamo et al., 2019; Campione et al., 2020; Renna et al., 2020; Marino et al., 2021). When administrating different protein sources to dairy cows, Sariçiçek (2000) observed that a diet supplemented with hazelnut OC positively affects milk fat content compared to a diet supplemented with urea (+0.87% point). The author hypothesised that this was probably due to the presence of undegradable protein in hazelnut OC, which was able to reach the small intestine. On the other hand, feeding hazelnut SK did not affect milk yield and composition in dairy cows (1 kg/head/day; Renna et al., 2020) and in dairy sheep (360 g/kg), but slightly reducing the protein content (−0.4% point; Campione et al., 2020). However, hazelnut SK were able to modify the FA profile of milk: C18:1 c9, PUFAs, CLA, and trans-FA increased whereas saturated FA, odd- and branched-chain FA (Campione et al., 2020; Renna et al., 2020), and C18:3 n-3 (Campione et al., 2020) decreased. These effects are likely attributable to the high content of C18:1 c9 and tannins in hazelnut SK, which modified the ruminal biohydrogenation and the composition of FA in derived products. Furthermore, hazelnut SK is a by-product rich in tocopherol, a powerful natural antioxidant. Cows fed with 1 kg/head/day of hazelnut SK had a higher tocopherol content in milk than cows fed with conventional diet (25.1 *vs* 20.7 mg/kg fat, respectively; Renna et al., 2020). Concerning the cheese processing and quality, feeding 360 g/kg of hazelnut SK increased the fat content of ewe cheese (31.94 *vs* 26.51 g/kg DM). As expected, the FA profile of cheese was similar to that of milk, with an increase in C18:1 c9, C18:1 t11, and CLA, known for their positive effects on human health (Nguye et al., 2019). Moreover, C14:0, C16:0, and cholesterol – known for their deleterious effects for human health – decreased in the cheese produced with milk from hazelnut SK-fed ewes (Marino et al., 2021). Feeding hazelnut SK increased the tocopherol content in Pecorino cheese compared to a conventional diet (18.1 *vs* 8.1 g of α-tocopherol/kg fat, respectively; Marino et al., 2021).

5. Monogastric animals

Several studies investigated the inclusion of nuts by-products in the diet of monogastric animals, mostly poultry (10 articles) and swine (8), and secondarily rabbits (2) and horses (2). The results of these studies are summarised in Table 7. As for other AIBP, the use of nuts by-products in the diet of monogastric animals is limited by their fibre content and the presence of ANF. Growth performances of poultry and swine decrease as dietary fibre increases, for which it is recommended not to exceed the inclusion level of 50–70 g/kg DM (Jha et al., 2019). However, dietary fibre is essential to maintain good intestinal health and feeding AIBP is a worthy strategy to increase the fibre content of the ration while cutting feed costs (Jha et al., 2019). Tannins, such as those contained in certain nuts by-products, are generally considered as ANFs for their negative effects on protein digestion and feed palatability. However, research has proven low tannin doses of about 5 g/kg and 10 g/kg in poultry and pig diets, respectively, to exert positive effects on gut health, microbial control, and productive performances (Huang et al., 2018). Therefore, the proper use of nuts by-products in the diet of monogastric animals requires the identification of a dietary level that avoids antinutritional effects while effectively harnessing the bioactive compounds contained therein.

5.1. Poultry

5.1.1. Almond

The dietary supplementation of almond HU as a partial substitute for corn was recently studied in broilers (Wang et al., 2021a; b) and laying hens (Wang et al., 2021c). In young broilers (19 d of age), the best performance was obtained with dietary levels of 50–60 g/kg (Wang et al., 2021a; b). At these doses, no negative effects on ileal DM and protein digestibility were observed (Wang et al., 2021b), whereas nutritional value and performance decreased with higher dietary levels. For instance, feed conversion ratio increased (1.5 *vs* 1.7), and ileal DM and protein digestibility decreased (70% *vs* 62% and 73% *vs* 64%, respectively) when broilers were fed 90 g/kg of almond HU (Wang et al., 2021b). These negative effects were likely due to the high CF content (up to 4.3%) that resulted from the inclusion of almond HU in the diet. In laying hens, a higher level of almond HU in the diet, up to 150 g/kg, can be adopted without any detrimental effect on laying performance and egg quality (Wang et al., 2021c). However, ration formulation may require an energy supplement, such as soybean oil, to balance the presence of indigestible fibre (Wang et al., 2021b; c). The studies by Wang et al. (2021b); c) also highlighted how the results may change when feeding by-products obtained from different cultivars and therefore with different chemical composition.

Almond OC has the potential of a protein feed for poultry. Arjomandi et al. (2015) replaced part of soybean meal with up to 300 g/kg of almond OC in the diet of quails with no negative effect on feed efficiency and body weight gain. Similarly, Moradi Yeganeh et al. (2021) observed similar growth performance between broilers fed a control diet and broilers fed a diet with up to 210 g/kg of almond OC in replacement of soybean meal. In both studies, methionine and lysine supplementations were necessary to compensate for the essential amino acids deficiency in almond OC. When the dietary supplementation of almond OC further increased to 280 g/kg, bodyweight gain decreased (−23%) and feed conversion ratio increased (+12%) compared to the control group (Moradi Yeganeh et al., 2021). Likely, this negative effect was due to the exceess of a critical dietary fibre threshold, which increased from 3.4% to 3.7% with 210 g/kg and 280 g/kg of almond OC, respectively. The phenolic compounds contained in almond by-products may also have exerted an antinutritional effect, but the authors did not assess their content in the diet.

5.1.2. *Hazelnut*

Studies on hazelnut by-products in poultry diet focused on the use of hazelnut OC as a protein feed in substitution of soybean meal. Lower final body weight (−10.6%) was reported in broilers fed with about 180 g/kg of hazelnut OC in replacement of 50% soybean meal (Erener et al., 2009). This effect was combined with a reduced feed intake, especially in the starter phase (Erener et al., 2009), probably because the tannins contained in hazelnut OC affected diet palatability. In addition, the fibre and tannin contents of hazelnut OC likely reduced nutrients utilization, but diet digestibility was not estimated in this study. The presence of indigestible fibre in the diet also caused an enlargement of gizzard and edible organs, thus reducing carcass yield (72.1% *vs* 70.6%; Erener et al., 2009). On the other hand, quails fed with up to 391 g/kg of hazelnut OC showed similar feed intake, final body weight, and carcass yield compared with the control group (Erener et al., 2003). In fact, quails can take advantage of higher levels of dietary fibre thanks to some physiological adjustment of the intestinal tract (Dias et al., 2020). Nonetheless, lysine, methionine, and threonine supplementation may be necessary to compensate for amino acids deficiencies (Erener et al., 2003, 2009). Regarding meat quality, there were no differences in the composition and mineral content of the meat of quails fed a diet including up to 300 g/kg of hazelnut OC compared to the meat of quails fed a soybean meal diet (Yalçin et al., 2005). Finally, laying performance and egg quality were not affected by the complete substitution of soybean meal with hazelnut OC in the diet of hens (Ozen and Erener, 1992) and quails (Erener et al., 2003).

5.1.3. *Walnut*

The growth performance of quails was not affected by the inclusion of up to 300 g/kg of walnut OC in replacement of part of dietary soybean meal (Arjomandi and Salarmoini, 2016). As for the inclusion of almond and hazelnut OC, the diet needed to be supplemented with essential amino acids such as lysine and methionine. Organs and carcass characteristics did not show any differences, whereas blood LDL, cholesterol, and triglycerides decreased with dietary walnut OC (Arjomandi and Salarmoini, 2016). However, the cholesterol content in quail's egg, as well as the protein content, was not affected by the dietary treatment. These results are in line with other studies testing the inclusion of nuts oil cake in poultry diet.

5.2. *Swine*

5.2.1. *Almond*

Almond HU can be used as an energy feed in growing pigs. In two different experiments, 150 g/kg of almond HU were administered to pigs in replacement of part of barley (Calvert and Parker, 1985; Homedes et al., 1993). The diet did not affect growth rate, final bodyweight, or carcass yield (Calvert and Parker, 1985). However, feed efficiency was reported to be 11% lower in pigs fed almond HU, due to a 10% reduction in net energy digestibility (Homedes et al., 1993). Analysis of carcass composition by body electrical conductivity scanning showed a higher protein content and a lower lipid content in pigs fed with almond HU, despite the similar weight (Homedes et al., 1993). Although the authors suggested that almond HU may have greater potential in sow and piglet nutrition, we are not aware of any research in this direction.

Finally, the digestibility of a diet that included up to 100 g/kg of kernel residues and broken almonds was assessed in pigs (Sol et al., 2016). This by-product is a quite energetic feed (ME 5.8 kcal/g) containing: OM 980, CP 169, EE 574, non-fibre carbohydrate 200, crude fibre 29, NDF 37, and ADF 26 g/kg DM (Sol et al., 2016, 2017). Nevertheless, OM and gross energy digestibility were reduced by the presence of this almond by-product, probably due to the lipids, undigestible fibre, and/or ANF contained therein. For this reason, after performing a regression analysis, Sol et al. (2016) suggested not to exceed the dose of 61 g/kg of residues of nuts and broken almonds in swine diet.

5.2.2. *Hazelnut*

Pigs were fed with 100 g/kg of in-shell cull hazelnut flour (Lammers et al., 2020). This by-product has intermediate chemical composition between kernels and shells: CP 76, crude fibre 495, NDF 687, ADF 567, EE 211, and lysine 2 g/kg DM (Lammers et al., 2020). The experimental diet did not negatively affect growth performance, carcass weight, or carcass fat, despite the unfavourable feed to gain ratio (+9%). Concerning meat quality, pigs fed with in-shell cull hazelnut flour showed lower SFAs content and higher MUFAs content. In particular, Lammers et al. (2020) observed a reduction in C16:0 and an increase in C18:1 *cis*9, which could contribute to improving the healthy traits of pork meat. These effects were likely due to the FA composition of this hazelnut by-product, rich in C18:1 *cis*9 (about 75% of total fat).

5.2.3. Walnut

The dietary inclusion of walnut OC in pigs was tested in mixture with extruded linseed. This combination could allow farmers to benefit from the antioxidant molecules contained in walnut OC, preserving the *n*-3 PUFA of linseed. A diet containing 90 g/kg of 8:1 linseed:walnut OC was offered to weaning piglets, resulting in higher bodyweight (+1.32 kg) and growth rate (+21 g/day) after 3 weeks (Gheorghe et al., 2018). Probably, the synergistic effect of linseed PUFAs and WOC bioactive compounds exerted an anti-inflammatory activity that improved growth performance. Moreover, after 21 days, piglets fed with the experimental diet had lower BUN, suggesting a better utilization of N (Gheorghe et al., 2018). Quite the opposite, 250 g/kg of 1:1 linseed:walnut OC in pigs did not influence BUN, but decreased total proteins and uric acid in plasma, indicating a metabolic deficiency (Târnoveanu et al., 2019). Unfortunately, no further information on diet digestibility and growth performance was provided. Concerning meat quality, Idriceanu et al. (2020) reported slight differences in the pH and colour of meat from pigs fed 80 g/kg of walnut OC mixed with linseed (3:5 w-w) compared to pigs fed a conventional diet. However, in their experiment, only 3 animals per feeding treatment were taken for meat analysis, which compromised the validity of these results.

5.3. Rabbits

Few studies have tested the inclusion of nuts by-products in rabbits' diet. In the study of Tor-Agbidye (1992), alfalfa meal was progressively replaced with almond HU in the pelleted diet of rabbits. Protein digestibility decreased (from 77% to 63%) with up to 400 g/kg of almond HU, but no detrimental effect on growth performance was observed (Tor-Agbidye, 1992). The authors reported that the inclusion of 600 g/kg of almond HU produced pellets that were too hard for weaning rabbits, causing low feed intake and growth performance.

The inclusion of 15 g/kg of hazelnut SK in a linseed-based diet reduced the oxidative stress markers in rabbits' blood serum (Candellone et al., 2019). Hazelnut SK was selected for its antioxidant function to prevent the negative effects of the degradation of linseed PUFAs in the diet of rabbits. The results indicated an increase in the antioxidant status in rabbits. Further research should investigate whether this feeding strategy could allow to delay lipid oxidation and off-flavour development in rabbit meat, while improving its nutritional properties and FA profile.

5.4. Horses

Horses have been little studied in feeding trials with nuts by-products. Replacing alfalfa and oat hay with up to 450 g/kg of dietary almond HU did not cause any detrimental effects, such as feed refusal, lip sores, colic, or impaction (Clutter and Rodiek, 1992). Dry matter and gross energy digestibility increased along with the dose of almond HU, probably as a consequence of the reduction in dietary ADF or due to a different eating behaviour (Hansen et al., 2020). However, protein digestibility decreased when almond HU were fed (Clutter and Rodiek, 1992), probably due to the antinutritional effect of the tannins contained therein.

6. Conclusions

The by-products of temperate-climate nuts can replace conventional feedstuff, provided that the diet is properly formulated. These by-products contain bioactive compounds, such as phenolic compounds, polyunsaturated fatty acids, and vitamins, which could provide benefits for animal health and final products. However, phenolic compounds such as tannins might limit the inclusion of nuts by-products in livestock feeding, especially for monogastric animals, because of their antinutritional properties. Ruminants demonstrated to better valorise these fibrous biomasses than monogastric animals.

Almond is the most cultivated nut in the world and produces a large amount of by-products. Almond hulls can replace concentrates or forages in the diet of dairy cows without reducing milk production, provided that the diet is formulated to avoid protein deficiencies. However, if this has to be s achieved by increasing protein sources such as soybean, it would cancel out the positive implication of the use of alternative agro-industrial by-products. Pistachio by-products contain a high quantity of tannins that might have negative effects on digestion and palatability. Nonetheless, it has been demonstrated that ensilaging or adding polyethylene-glycol reduces these negative effects and allows the benefits of low-to-moderate doses of tannins to be exploited. Feeding hazelnut skin can improve the fatty acid profile of meat and milk, making it healthier for human consumption, as well as the antioxidant stability of products. Moreover, the antioxidant effect of the tocopherols contained in hazelnut skin tannins may contribute to the reduction of oxidative stress in animals. Nuts oil cake can partially replace soybean meal as protein source for poultry and swine, paying due attention to dietary fibre, essential amino acids, and antinutritional factors. Further research should investigate its potential in the diet of sows and piglets.

A weakness highlighted in this review is the great variability in the nutritional quality of the same by-product. The chemical composition of nuts by-products is very irregular, due to: cultivar, environment (*i.e.*, soil, agronomic practices, climate conditions), or conservation technique. This obstacle makes it necessary to perform chemical analyses for each by-product batch before feeding it to animals. A second issue that limits the valorisation of these by-products is the lack of information on production volumes and market flows. While it is easy to know how much by-product can be obtained from each industrial process, it is difficult to quantify the quota of nuts that are destined for fresh consumption rather than for confectionery or oil extraction. Furthermore, it must be considered that other sectors than livestock feeding could benefit from the use of these by-products, such as fertilizers, biofuels, or cosmetic industries.

Research on the use of these alternative by-products in animal feeding is essential to expand the available knowledge and improve the feed resilience of livestock systems, even if only at the local level. Some nuts by-products, such as chestnut by-products or several cull nuts, have yet to be investigated. More studies are needed to establish the benefits for animal health and product quality provided by nuts by-product. Further research should also address the health hazards associated with the contamination of nuts by-products with pesticide residues, heavy metals, harmful bacteria, or mycotoxins. Finally, environmental impact assessments, such as LCA (life cycle analysis), should be included in the evaluation of these alternative by-products to determine the actual sustainability of their use as animal feedstuff.

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CRediT authorship contribution statement

Martino Musati: Investigation, Writing – original draft. **Ruggero Menci:** Visualization, Supervision, Writing – review & editing. **Giuseppe Luciano:** Conceptualization, Writing – review & editing. **Pilar Frutos:** Writing – review & editing. **Alessandro Priolo:** Conceptualization, Writing – review & editing. **Antonio Natalello:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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