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Enrichment of ruminant meats with health enhancing fatty acids and antioxidants: feed-based effects on nutritional value and human health aspects – invited review

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Optimising resource use efficiency in animal- agriculture-production systems is important for the economic, environmental, and social sustainability of food systems. Production of foods with increased health enhancing aspects can add value to the health and wellbeing of the population. However, enrichment of foods, especially meat with health enhancing fatty acids (HEFA) increases susceptibility to peroxidation, which adversely influences its shelf life, nutritional value and eating quality. The meat industry has been challenged to find sustainable strategies that enhance the fatty acid profile and antioxidant actions of meat while mitigating oxidative deterioration and spoilage. Currently, by-products or co-products from agricultural industries containing a balance of HEFA and antioxidant sources seem to be a sustainable strategy to overcome this challenge. However, HEFA and antioxidant enrichment processes are influenced by ruminal lipolysis and biohydrogenation, HEFA-antioxidant interactions in rumen ecosystems and muscle biofortification. A deep understanding of the performance of different agro-by-product-based HEFA and antioxidants and their application in current animal production systems is critical in developing HEFA-antioxidant co-supplementation strategies that would benefit modern consumers who desire nutritious, palatable, safe, healthy, affordable, and welfare friendly meat and processed meat products. The current review presents the latest developments regarding discovery and application of novel sources of health beneficial agro-by-product-based HEFA and antioxidants currently used in the production of HEFA-antioxidant enriched ruminant meats and highlights future research perspectives.

KEYWORDS

red meat, dietary means, forages, phytonutrients, conjugated linoleic acid, omega-3 fatty acids, antioxidants, muscle fortification

1 Introduction

There are many breeds and genotypes within the ruminant animal species of sheep, goats and cattle around the world, each of them is adapted to the different environments they live in and the diets they consume. Ruminant animals obtain their nutrients from fresh forage materials of native rangelands or cultivated pastures, crop residues, cereal grains, preserved forages and agri-food by-products (Ponnampalam et al., 2022), and nutrition and feeding strategies play a major role in the wellness, productivity, and survival of animals. Numerous studies have investigated the effect of feeding systems and feed composition on the fat content, fatty acid (FA) composition and antioxidant status of meat in ruminants (Scollan et al., 2006; Chilliard et al., 2007; Noci et al., 2011; Chauhan et al., 2014; Berthelot and Gruffat, 2018; Vahmani et al., 2020). Dietary proteins, lipids and carbohydrates are vital for ruminant growth and development. Equally, vitamins, minerals and health enhancing fatty acids (HEFA) are crucial for animal health, well-being and product quality (Kaur et al., 2014; Ponnampalam et al., 2021a; Guo et al., 2023; Kearns et al., 2023b). The HEFA include the parent (precursors), their products (derivatives) as well as their biohydrogenation intermediates (BHI). These in turn include alpha-linolenic acid (ALA, C18:3n-3), eicosapentaenoic acid (EPA, C20:5n-3), docosapentaenoic acid (DPA, C22:5n-3), docosahexaenoic acid (DHA, C22:6n-3), linoleic acid (LA, C18:2n-6), rumenic acid (RA, cis(c)9, trans(t)11-18:2), and trans vaccenic acid (TVA, cis(c)9, trans (t)11-18:1). The economic return of animal production systems is largely dependent on the yield, quality, nutritional value and storage stability of the meat produced by the flock or herd.

Red meat, obtained from lamb/mutton, beef, and chevon, is rich in vital nutrients, including a high amount of highly digestible proteins, containing all essential amino acids to meet human requirements, B vitamins (mainly vitamin B12), zinc, iron, and selenium (Klurfeld, 2018). Red meat is one of the most important animal source foods in many countries all over the world. However, epidemiological data from meta-analyses shows that excessive consumption of red meat and processed meat can have deleterious effects, including an increased risk of colorectal cancer and premature death (Schwingshackl et al., 2017; WCRF et al., 2018), leading to recommendations to limit consumption to 500 g/week for red meat and 150 g/week for processed meat (Prache et al., 2022a). North America, Europe and Oceania regions consume large quantities of red and white meat, African regions consume the least amount, and the Asia and Latin America regions consume moderate amounts. The per capita consumption per year of beef-veal, sheep meat (lamb and mutton), poultry meat and pork worldwide, and within major regions of the world is shown in Figure 1. As goat meat intake is very small in quantity around the world and mostly associated with some ethnic groups within countries, it was not shown. The per capita consumption of red meat around the world has increased from 10 to 20 kg of meat between 1961 and 2020 (Ritchie et al., 2019).

The mean consumption of unprocessed and processed red meat per person across countries varies due to affordability, availability, and preference. The low-fat content (of particular cuts) relevant to all meats has great importance due to the links found between meat FA consumption and prevalence of chronic disease (Bernstein et al., 2010; Abid et al., 2014). Table 1 below provides some information on consumption of beef-veal, sheep meat (lamb-mutton), poultry meat and pork from developed and developing countries around the world, expressed in retail weight.

Ruminant meat is a good source of HEFA. Linoleic acid and ALA are parent (precursor) fatty acids, which cannot be synthesised by the animal and human body and must be obtained from the diet (Kaur et al., 2014; Ponnampalam, 1999). These two FA are vital for the synthesis of their longer chain polyunsaturated fatty acid (PUFA) derivatives and their bioactive intermediates in the rumen and fortification in animal tissues (Ponnampalam et al., 2021b). In addition, ruminant meats contain nutrient antioxidants such as vitamins A, C and E, and the minerals copper, zinc and selenium (Bourre, 2011; Cabrera and Saadoun, 2014), which scavenge the free radicals and reactive oxygen species (ROS) in the cell, thereby mitigating oxidative stress and its consequences in the body (Zehiroglu and Ozturk Sarikaya, 2019). Both HEFA and antioxidants play a crucial role in the maintenance and/or enhancement of animal welfare, meat shelf life and sensory attributes and health of human beings (Scollan et al., 2006; Kurutas, 2015; Lauridsen, 2019; Ponnampalam et al., 2021a; Ponnampalam et al., 2022). Therefore, enriching ruminant meat, which is consumed by the majority of the world population, with HEFA and antioxidants could improve the nutritional value (i.e., health aspects), quality (i.e., sensory), and storage stability (i.e., shelf

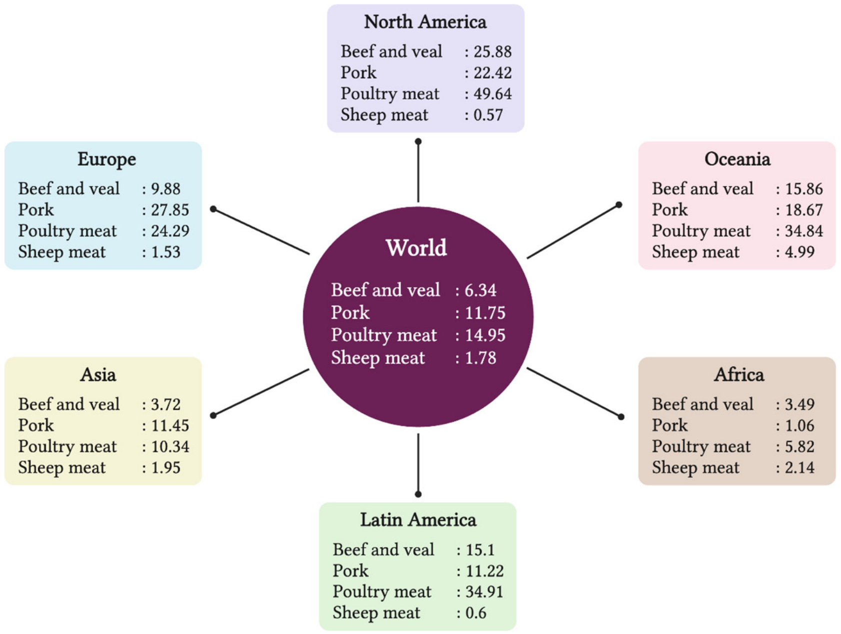

FIGURE 1
The per capita consumption (kg / year) of beef-veal, sheep meat (lamb and mutton), poultry and pork of world and major regions of world. Source: OECD/FAO (2021), OECD Agriculture statistics (database), http://dx.doi.org/10.1787/agr-outl-dataen.

life) of meat and eventually benefit the health of human beings as illustrated in Figure 2. This review aims to provide an update on aspects of various diets and feeding strategies contributing to the enrichment of HEFA and antioxidants in meat from sheep, goats and cattle, enabling improvement in the nutritional value, quality and health aspects of red meat that in turn may enhance health and well-being of humans upon consumption.

2 Feed-based enrichment of health enhancing fatty acid concentrations in red meat from sheep, goats and cattle

Meat from ruminant and monogastric animal species contributes important sources of nutrients from childhood to old age in many communities in developed and developing countries (FAO, 2011; Pereira and Vicente, 2013; FAO, 2017). Red meat from ruminants can offer balanced nutrient profiles and promote consumer health in many societies around the world (Pereira and Vicente, 2013), provided it is not consumed in excess (Prache et al., 2022a). Nutrient composition of meat is influenced by the type of diet that the animals consume. For example, feeding grain-based diets to ruminants increases intramuscular fat (i.e., marbling), omega(n)-6 FA concentrations and the n-6:n-3 ratio in meat (Aurousseau et al., 2004; Ponnampalam et al., 2017; Chikwanha et al., 2018, 2007; Berthelot and Gruffat, 2018; Gruffat et al., 2020; Clinquart et al., 2022; Davis et al., 2022). The latter effects are mainly due to variation in diet composition and nutrient availability of feeds affecting the ruminal biohydrogenation process, digestion and absorption of nutrients in the gastro-intestinal tract (GIT) of the host animal and subsequent metabolism in the body, determining the availability of energy and nutrients for the synthesis of biochemical components in meat.

There are many reasons for the variation in HEFA concentrations in meat, mainly determined by the ruminal lipolysis and biohydrogenation process of microbial activity. Lipids/fats in the diet can be categorised as protected or unprotected, depending on their susceptibility to microbial degradation and biohydrogenation in the rumen. Dietary fats can be protected naturally (e.g., feeding whole oilseeds) or by chemical interventions (fat emulsification or encapsulation within proteins) to form calcium soaps or amides, which protect against rumen degradation. Protected fats are conditioned to limit their degradation in the rumen while unprotected fats are subjected to ruminal degradation, whereby PUFA are hydrogenated into SFA and free FAs as a result of ruminal lipolysis by microbes. Biohydrogenation is not comprehensive; a portion of unprotected fats may by-pass degradation in the rumen, thereby becoming available for absorption and deposition in muscle and other tissues.

Lipids are either consumed or synthesised *de novo* and it should be noted that the digestion and absorption of lipids (or fats) in ruminant and monogastric animals are not similar. This is due to their feeding nature and structure of digestive systems. Ruminant animals accustomed to consuming diets containing 1–4% fat, and lipid supplements fed to ruminants above 5–6% on a dry matter basis may cause negative effects on rumen microbial activity, affecting feed intake and animal productivity. With monogastric animals having a stomach as one organ for temporary storage of diet (fats) in the absence of rumen microbial activity, they can handle greater amounts of lipids in their diet and the fat deposition in meat resembles dietary lipid composition, while this is not the case for ruminants. More

TABLE 1 Per capita consumption (kg / year) of beef and veal, pork, poultry meat and sheep meat (lamb-mutton) from developed and developing countries around the world.

Countries	Per capita consumption of meat			
	Beef and veal	Pork	Poultry meat	Sheep meat
Argentina	35.55	11.51	40.45	0.96
Australia	23.51	23.93	45.77	6.94
Brazil	21.56	12.64	44.34	0.6
Canada	18.9	15.64	34.91	0.88
Chile	23.14	20.74	34.88	0.39
China	4.73	28.71	13.6	3.27
Colombia	9.67	9.33	31.03	0.02
Egypt	6.19	0.02	12.69	0.53
Ethiopia	2.5	0.01	0.49	1.98
European Union	10.41	33.18	23.91	1.31
India	0.58	0.18	2.38	0.52
Indonesia	2.01	0.68	12.61	0.45
Iran	4.7	0	22.98	3.54
Israel	25.08	0.99	63.84	1.52
Japan	7.29	16.65	17.73	0.16
Kazakhstan	21.8	5.71	22.91	7.95
Korea	12.08	30.35	20.08	0.37
Malaysia	5.1	5.63	44.05	0.89
Mexico	8.81	15.37	32.35	0.72
New Zealand	11.21	17.99	39.68	3.19
Nigeria	1.09	1.09	0.99	1.7
Norway	14.02	22.05	16.87	4.54
Pakistan	7.17	0	7.07	2.97
Paraguay	16.61	7.18	8.51	0.37
Peru	4.13	4.38	48.83	1.01
Philippines	2.33	10.66	14.05	0.27
Russian Federation	9.07	22.68	26.67	1.3
Saudi Arabia	4.2	0.31	37.22	4.53
South Africa	11.35	4.33	33.72	2.56
Switzerland	13.91	21.24	12.72	1.29
Thailand	1.13	9.46	7.24	0.03
Türkiye	7.54	0	17.38	1.19
Ukraine	4.72	13.84	21.19	0.19
United Kingdom	11.56	16.21	27.75	3.92
United States	26.67	23.2	51.33	0.53
Vietnam	5.14	31.42	15.2	0.19

Meat consumption expressed in retail weight. Source: OECD/FAO (2021), OECD Agriculture statistics (database), http://dx.doi.org/10.1787/agr-outl-dataen.

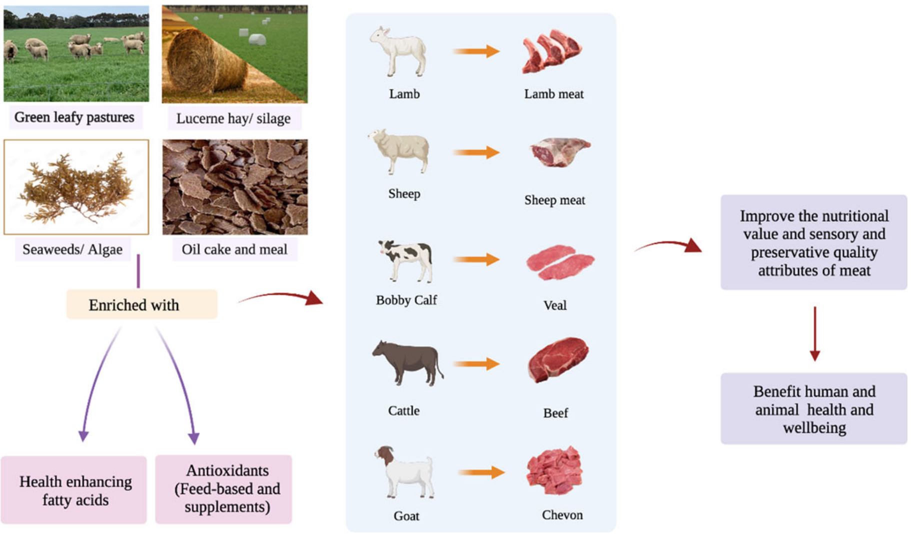

FIGURE 2
Schematic diagram showing pathways to enrich meat from ruminants with health enhancing FA and antioxidants delivering improved nutritional value and health aspects for consumers.

details on ruminal lipolysis, biohydrogenation and digestion process of dietary lipids can be found elsewhere (Swanson, 2019; Ponnampalam et al., 2021b).

2.1 Influence of diets on health enhancing fatty acids in lamb and mutton

Levels of HEFA in ruminant meat are largely dependent on the type of dietary fat consumed, the duration of feeding and ruminal biohydrogenation of PUFA. In this regard, a variety of nutritional strategies have been employed to increase HEFA deposition in sheep meat (i.e., lamb and mutton), which have been summarised in Table 2.

Meat from pasture-fed animals contains higher *n*-3 PUFA contents compared to grain-fed animals (Aurousseau et al., 2004; Nuernberg et al., 2005; Hajji et al., 2016, 2007; Berthelot and Gruffat, 2018; Gruffat et al., 2020), due to the naturally high levels of ALA in fresh pasture, a precursor for endogenous production of EPA, DPA and DHA (Ponnampalam et al., 2021b). It also contains a lower proportion of C16:0, which is pro-atherogenic (Berthelot and Gruffat, 2018). Grain supplementation at pasture diminishes these advantages, especially as the quantity of concentrate consumed increases (Montossi et al., 2013; Berthelot and Gruffat, 2018). Prolonged finishing periods on grain post-grazing diminishes *n*-3 PUFA accumulated in the meat, with lower ALA, EPA and DHA and their BHI such as CLAs (e.g., RA) and TVA levels observed in lamb meat (Aurousseau et al., 2007; Scerra et al., 2011). Conversely, there is a lack of data on the effect of the length of time an animal is finished on pasture pre-slaughter on the HEFA concentration in sheep meat. Pasture type can affect the HEFA composition of meat. Grazing lambs on legumes like lucerne and red clover (Fraser et al., 2004) or white clover (Lourenço et al., 2007) increased ALA levels in meat compared to lambs grazing grasses like perennial ryegrass. Similarly, meat from lambs grazing chicory/arrow leaf clover had higher concentrations of *n*-3 PUFAs including ALA, EPA and DHA compared to lambs grazing brassica (De Brito et al., 2017). Lambs grazing botanically diverse pastures with phenol-rich plants produce meat richer in PUFA, ALA and LA than lambs grazing intensively managed pastures, with the concentration of these FA in the meat being linearly related to the phenolic concentration of the pasture (Willems et al., 2014). Plant secondary metabolites (polyphenol oxidase, flavonoids, tannins, essential oils and saponins) in legume and forb species can influence microbial biohydrogenation in the rumen, positively affecting beneficial *n*-3 PUFA and BHI outflow (Campidonico et al., 2016; Chikwanha et al., 2018; Frutos et al., 2020). Moreover, condensed tannins found in certain legumes can improve the lamb flavour by inhibiting the ruminal synthesis of skatole and indole, which are faecal-smelling compounds (Scollan et al., 2008; Girard et al., 2016; Rivaroli et al., 2019). Note here that sheep meat contains more HEFA than beef, due to lower ruminal biohydrogenation and a more selective eating behaviour of the animal (Prache et al., 2022b).

Generally, ruminants grazing fresh pasture consume higher amounts of *n*-3 PUFA compared to ruminants fed conserved forages (Ciftci et al., 2010) or total mixed ration (TMR) diets (Aurousseau et al., 2004, 2007; Berthelot and Gruffat, 2018; Gruffat et al., 2020). However, supplementation with *n*-3 PUFA rich oilseeds, marine- and plant-sourced oils and by-products have sometimes yielded more positive results. For example, addition of flaxseed to lamb diets resulted in increased contents of beneficial *n*-3 PUFA (i.e., ALA, EPA and DPA) in lamb and mutton (Noci et al., 2011; Ponnampalam et al., 2015; Urrutia et al., 2015; Berthelot and Gruffat, 2018). Diets supplemented with fish/algae oils increased long-chain *n*-3 PUFA levels such as EPA and DHA in lamb meat (Ponnampalam et al., 2016; Parvar et al., 2017), particularly when fed in an encapsulated form to protect against rumen

TABLE 2 Influence of diet on the health enhancing fatty acid composition (% of total fatty acids) of sheep meat.

Diet	Fatty acid (%)									Reference
	TVA	RA	LA	ALA	EPA	DPA	DHA	*n*-3	*n*-6	
Forage										
Grass-based permanent pasture	2.92	2.01	0.85	2.97	1.48	0.85	0.74	3.50	4.35	Rodríguez et al. (2020)
Chicory/plantain	2.40	1.98	0.76	3.59	1.91	0.92	0.99	4.12	5.04	
Perennial ryegrass pasture	2.92	1.46	–	1.39	–	–	–	2.40	5.88	Kliem et al. (2018)
Biodiverse pasture	2.40	1.30	–	1.66	–	–	–	2.70	6.74	
Botanically diverse	2.22	0.90	7.06	2.64	2.76	2.69	0.43	–	–	Lourenço et al. (2007)
Leguminosae-rich pasture	2.41	0.74	5.28	3.99	1.09	1.08	0.29	–	–	
Intensive ryegrass pasture	2.74	0.90	3.37	2.59	1.33	1.26	0.34	–	–	
Lucerne pasture	3.10	1.09	4.02	2.72	0.90	0.80	0.25	–	–	Fraser et al. (2004)
Red clover pasture	3.71	1.33	4.47	2.86	1.03	0.90	0.27	–	–	
Perennial ryegrass pasture	3.65	1.23	2.91	2.07	0.93	0.82	0.24	–	–	
Forage vs. Concentrate										
Concentrate + hay	–	0.21	4.30	0.29	0.28	0.63	0.21	1.41	6.94	Gruffat et al. (2020)
Alfalfa pasture	–	0.65	3.94	0.02	1.03	1.20	0.50	4.19	9.06	
Alfalfa pasture + sainfoin pellets	–	0.49	4.48	0.36	1.29	1.47	0.62	5.17	7.96	
Concentrate	–	0.42	3.82	0.44	0.18	0.46	0.80	0.99	5.37	Hajji et al. (2016)
Grass pasture	–	0.70	7.92	2.27	1.13	1.71	0.27	4.26	11.96	
Concentrate	0.42	0.59	12.55	0.51	0.38	–	0.28	1.77	22.24	Scerra et al. (2011)
Grass pasture	1.48	1.38	9.06	3.13	1.25	–	1.12	6.09	18.46	
Grass pasture	4.40	1.10	5.80	2.60	1.80	2.40	0.60	7.60	9.90	Aurousseau et al. (2007)
Grass pasture/short period on concentrate	4.70	1.00	5.70	1.70	1.30	1.80	0.50	5.30	9.10	
Grass pasture/long period on concentrate	2.00	0.90	5.70	1.20	1.20	1.50	0.50	4.80	9.50	
Concentrate	1.60	0.70	6.40	1.30	1.00	1.40	0.50	4.40	10.10	
Concentrate	3.80	1.08	6.60	1.20	1.40	1.20	0.50	4.30	10.10	Nuernberg et al. (2005)
Grass pasture	5.70	1.90	5.00	2.40	1.80	1.40	0.80	6.30	7.80	
Oil Supplementation										
TMR	–	–	7.26	0.45	0.48	0.29	0.32	1.54	8.94	Parvar et al. (2017)
TMR + 3% fish oil	–	–	9.22	0.82	1.94	0.9	1.78	5.54	10.91	
TMR + 3% canola oil	–	–	9.53	1.09	0.68	0.44	0.44	2.65	11.04	
TMR + 3% soybean oil	–	–	9.94	0.86	0.28	0.53	0.36	2.03	11.32	
TMR + 1.5% fish oil/1.5% canola oil	–	–	12.03	0.84	1.8	0.81	1.12	4.57	14.07	
TMR + 1.5% fish oil/1.5% soybean oil	–	–	10.52	0.82	0.72	0.8	0.78	3.11	12.16	
TMR + 1.5% soybean oil/1.5% canola oil	–	–	12.41	0.66	0.8	0.72	0.75	2.93	14.85	
Concentrate	3.79	0.26	8.79	0.53	0.19	0.42	0.12	1.43	13.38	Urrutia et al. (2015)
Concentrate + linseed	6.65	0.22	9.4	1.84	0.42	0.6	0.15	3.25	14.73	
Concentrate + chia seed	5.57	0.25	9.35	1.73	0.36	0.54	0.15	3.14	15.29	
Annual ryegrass hay/clover hay	–	–	2.94	1.35	0.69	0.55	0.30	–	–	Ponnampalam et al. (2015)
Annual ryegrass hay/clover hay + flaxseed	–	–	3.19	2.29	0.70	0.43	0.26	–	–	

(*Continued*)

TABLE 2 Continued

Diet	Fatty acid (%)									Reference
	TVA	RA	LA	ALA	EPA	DPA	DHA	*n*-3	*n*-6	
Oil Supplementation										
Annual ryegrass hay/clover hay + algae supplement	–	–	2.73	1.25	0.85	0.38	2.47	–	–	
Annual ryegrass hay/clover hay + flaxseed/ algae supplement	–	–	2.84	1.61	0.67	0.32	1.93	–	–	
Concentrate	0.93	0.73	11.88	0.75	0.64	1.46	0.89	3.87	20.5	Nudda et al. (2015)
Concentrate + linseed	2.82	1.55	12.60	1.79	0.90	1.43	0.84	5.12	19.71	
Forage/concentrate + 3% palm oil	0.57	0.36	8.41	0.43	0.44	1.02	0.62	–	–	Gallardo et al. (2014)
Forage/concentrate + 3% olive oil	1.27	0.7	8.32	0.50	0.58	1.23	0.72	–	–	
Forage/concentrate + 3% fish oil	3.75	1.66	7.82	0.96	2.72	2.21	1.53	–	–	
Concentrate + rumen protected saturated fat	2.85	0.82	3.45	0.50	0.07	0.20	0.04	0.87	4.31	Noci et al. (2011)
Concentrate + camelina oil	4.61	0.95	2.86	1.27	0.11	0.20	0.05	1.75	3.70	
Concentrate + linseed oil	5.28	0.98	3.01	1.74	0.12	0.21	0.03	2.18	3.72	
By-products										
TMR	1.44	1.07	10.67	0.67	–	–	–	–	–	Bennato et al. (2023)
TMR + 10% grape pomace	2.32	1.22	11.97	0.61	–	–	–	–	–	
Concentrate	0.73	0.35	5.37	0.37	0.13	0.26	0.09	0.86	7.29	Natalello et al. (2019)
Concentrate + 20% pomegranate by-product	1.38	0.94	7.09	0.51	0.20	0.36	0.11	1.19	9.67	
Concentrate	0.67	0.18	10.48	0.26	0.16	0.40	0.10	–	–	Gómez-Cortés et al. (2019)
Concentrate + 50% camelina meal	1.26	0.28	8.99	0.25	0.15	0.38	0.14	–	–	
Concentrate + camelina meal/husks	3.59	0.79	11.12	0.34	0.13	0.39	0.11	–	–	
Concentrate	1.88	–	7.36	0.41	0.19	0.57	0.13	–	–	Asadollahi et al. (2017)
Concentrate + 7% roasted canola seed	2.02	–	9.77	0.64	0.23	0.65	0.19	–	–	
Concentrate + 36% sugar beet pulp	1.71	–	6.26	0.53	0.20	0.56	0.14	–	–	
Concentrate + 7% roasted canola seed + 36% sugar beet pulp	2.03	–	6.5	0.68	0.23	0.67	0.14	–	–	

TVA, trans-vaccenic acid; RA, rumenic acid; LA, linoleic acid; ALA, linolenic acid; EPA, eicosapentaenoic acid; DPA, docosapentaenoic acid; DHA, docosaehexanoic acid; n-3, omega-3 fatty acids; n-6, omega-6 fatty acids.
TMR, total mixed ration.

biohydrogenation (Bessa et al., 2015). Supplementation of forage diets with *n*-6 rich oils (sunflower/soybean) has been shown to increase proportions of LA, RA and TVA, as well as other CLA isomers in lamb meat when compared to supplementation with *n*-3 PUFA rich oil sources (Chikwanha et al., 2018). Feeding lambs by-products such as grape/pomegranate pomace, soyabean hull and camelina meal, which are rich in antioxidants (polyphenols, flavonoids, anthocyanidins and tannins) led to enriched levels of ALA and total *n*-3 PUFA in meat (Gómez-Cortés et al., 2019; Natalello et al., 2019; Bennato et al., 2023). In summary, feeding pasture or high forage diets rich in *n*-3 PUFA leads to higher contents of health beneficial *n*-3 PUFA (ALA, EPA and DHA) and their BHI (RA and VA) in lamb meat. When high forage diets are fed along with *n*-6 PUFA rich sources, high concentrations of RA and VA are observed in meat, as *n*-6 rich dietary sources are more effective at increasing RA and VA levels compared to *n*-3 rich dietary sources (Bessa et al., 2015; Chikwanha et al., 2018). Total mixed rations and grain-based diets may require the addition of a *n*-3 PUFA and forage sources to improve HEFA levels in sheep meat.

Meat from suckling lambs is widely consumed in southern Europe. In this case, lambs are considered as monogastric, and their meat FA profile reflects the feed-milk profile. Feeding ewes on good quality pastures (Joy et al., 2012), particularly biodiverse pastures containing various legume species (Cabiddu et al., 2005) has been shown to improve the HEFA content of meat from their lambs. The inclusion of n-3 PUFA rich oilseeds (Gallardo et al., 2015; Nudda et al., 2015) or marine oils (Gallardo et al., 2014) in ewe diets has also been shown to improve the HEFA content of lamb meat, but the inclusion of grape by-products did not significantly alter the HEFA content of lamb meat (Correddu et al., 2023).

2.2 Influence of diets on health enhancing fatty acids in beef and veal

The FA profile of veal and beef is largely influenced by diet, with forage finishing being the most practical strategy to increase the proportions of PUFAs, particularly *n*-3 PUFA and their BHIs (mostly RA and TVA), as previously reviewed by numerous authors (Mapiye et al., 2015; Vahmani et al., 2015; Berthelot and Gruffat, 2018). Therefore, only recent studies relating to the dietary manipulation of HEFA in beef have been included in Table 3.

The extent of these changes in beef is mainly dependent on the PUFA content of forage, in particular ALA, which is the predominant PUFA in most forage species (Dierking et al., 2010), and on finishing duration on these forages pre-slaughter (Noci et al., 2005). Noci et al. (2005) observed a linear increase in the n-3 PUFA content of beef up to 158 days of grazing. In general, fresh forages and pastures have higher contents of total lipids and total PUFA compared to conserved forages (i.e., silage and hay). This is mainly due to oxidative degradation of PUFA during haymaking and ensiling processes. In terms of species, legumes generally have higher contents of total FA, total PUFA and *n*-3 PUFAs, particularly ALA, compared to most grass species. However, grass offers greater levels of ALA than most cereal grains, which are the main sources of n-6 PUFA, mostly LA (Boufaïed et al., 2003). Consequently, beef from cattle grazing pastures containing white or red clover has higher proportions of *n*-3 PUFAs, along with a lower *n*-6:*n*-3 ratio (Lee et al., 2009; Berthelot and Gruffat, 2018; Moloney et al., 2018). Additionally, grazing steers on multispecies pasture consisting of different grasses, legumes and forbs resulted in beef with higher levels of LA, ALA and a higher n-6:n-3 ratio compared to beef from steers grazing perennial ryegrass (Kearns et al., 2023a). Given fresh forages and pastures contain higher concentrations of ALA, grazing is more effective in increasing n-3 PUFA and their respective BHIs while lowering the *n*-6:*n*-3 ratio in beef compared to feeding conserved forages and high-grain diets.

Conversely, LA is the predominant FA in grain-based diets which leads to increased *n*-6 PUFA contents, particularly LA, and higher *n*-6:*n*-3 ratios in grain-finished feedlot fed beef (Vahmani et al., 2015; Berthelot and Gruffat, 2018; Klopatek et al., 2022). Despite feedlot beef having a higher *n*-6:*n*-3 ratio (5:1 to 8:1) than forage-finished beef (1:1 to 3:1), the ratios are still lower than typical chicken and pork (15:1 to 19:1) (Dugan et al., 2015; Kim et al., 2020). In fact, consuming either forage or grain-finished beef may help to reduce the *n*-6:*n*-3 ratio in western diets which is currently estimated to be around 20:1 (DiNicolantonio and O'Keefe, 2021). In addition to forage-finishing strategies, attempts have been made to increase the amount of *n*-3 PUFAs in beef through supplementing diets with *n*-3 PUFA rich oils or oilseed meals (e.g., canola oil or canola meal). However, limited *n*-3 PUFA enrichments can be achieved using this approach because of extensive biohydrogenation of PUFA in the rumen (Vahmani et al., 2015) when compared with supplementing marine-based (algae) or chemically protected *n*-3 PUFA sources. Moreover, PUFA supplementation, particularly LA in forage diets often results in an increased tissue deposition of BHI, particularly TVA and RA, while supplementation in high-grain diets yields *t*10-18:1 and *t*10,*c*12-CLA (Vahmani et al., 2020; Alves et al., 2021). Given recent studies have shown that ruminant-derived trans FAs such as t10-18:1 (Vahmani et al., 2020) have similar adverse effects to that of industrial trans FAs (Verneque et al., 2022), it would be of importance to determine if the health value of beef enriched with *n*-3 PUFA is still maintained when different proportions of trans FAs are present.

2.3 Influence of diets on health enhancing fatty acids in chevon

Goat meat (i.e., chevon) has less fat than other red meat from ruminants (James and Berry, 1997), having about 50% less intramuscular fat (IMF) than beef and lamb with similar protein contents (Webb et al., 2005). In general, chevon contains higher

TABLE 3 Influence of diet on the health enhancing fatty acid composition (% of total fatty acids) of beef from ruminants.

Diet	Fatty acid (%)									Reference
	TVA	RA	LA	ALA	EPA	DPA	DHA	*n*-3	*n*-6	
Forage										
Perennial ryegrass pasture	–	–	3.64	0.82	0.52	1.02	–	2.77	5.58	Kearns et al. (2023a)
Perennial ryegrass/white clover pasture	–	–	4.33	1.12	0.65	1.20	–	3.40	6.54	
Multispecies pasture	–	–	5.91	1.56	0.66	1.25	–	3.93	8.47	
Rangeland pasture	2.08	0.63	3.97	1.52	0.89	0.95	–	3.52	6.02	Klopatek et al. (2022)
Rangeland pasture/irrigated pasture	2.44	0.58	2.48	1.09	0.41	0.63	–	2.24	3.71	
Perennial ryegrass/white clover pasture	–	0.46	2.11	1.13	0.58	0.93	–	2.92	3.19	Lee et al. (2021)
Permanent pasture	–	0.52	2.01	1.17	0.66	0.98	–	3.11	3.06	
Perennial ryegrass pasture	–	0.47	3.08	1.61	0.48	0.69	0.05	3.00	3.76	Moloney et al. (2018)
Perennial ryegrass/white clover pasture	–	0.58	2.51	1.23	0.48	0.61	0.06	2.52	3.15	

(Continued)

TABLE 3 Continued

Diet	Fatty acid (%)									Reference
	TVA	RA	LA	ALA	EPA	DPA	DHA	*n*-3	*n*-6	
Forage										
Grass silage	0.91	0.22	1.87	0.71	0.31	0.55	0.05	1.77	2.97	Lee et al. (2009)
Red clover silage	0.92	0.17	2.64	1.54	0.44	0.74	0.06	2.26	3.01	
0 days on perennial ryegrass	1.35	0.50	2.64	1.03	0.22	0.38	0.13	1.59	3.50	Noci et al. (2005)
40 days on perennial ryegrass	1.93	0.50	2.52	1.14	0.28	0.43	0.16	1.90	3.80	
90 days on perennial ryegrass	2.27	0.57	2.35	1.02	0.25	0.43	0.17	1.88	3.06	
158 days on perennial ryegrass	3.01	0.71	2.49	1.29	0.30	0.54	0.21	2.37	3.46	
Forage vs. Concentrate										
Silage + barley concentrate	–	0.18	4.07	0.61	0.20	0.36	0.02	1.21	5.35	Siphambili et al. (2022)
Silage + maize meal concentrate	–	0.21	5.37	0.72	0.33	0.55	0.06	1.69	7.13	
Silage + flaked meal concentrate	–	0.19	6.64	0.81	0.31	0.58	0.06	1.78	8.48	
Whole corn grain	–	0.21	5.67	0.22	0.17	0.40	0.09	0.92	8.15	Fruet et al. (2018)
Legume/grass pasture + whole corn gain supplementation	–	0.33	3.71	0.90	0.53	0.99	0.24	2.44	6.98	
Legume/grass pasture	–	0.41	4.22	1.59	0.66	1.21	0.10	3.60	6.79	
Concentrate	–	–	2.25	0.17	0.05	0.03	–	0.27	2.95	Hwang and Joo (2017)
Grass pasture	–	–	1.93	0.97	0.12	0.08	–	1.22	2.48	
Mixed pasture	3.58	0.64	2.59	1.17	0.54	0.85	0.09	2.65	3.46	Duckett et al. (2013)
Alfalfa pasture	3.32	0.61	2.85	1.32	0.60	0.91	0.10	2.92	3.79	
Pearl Millet pasture	3.56	0.70	2.27	1.06	0.49	0.76	0.07	2.39	3.08	
Concentrate	0.15	0.26	2.62	0.24	0.09	0.21	0.03	0.56	3.18	
Oil Supplementation										
Silage/concentrate	7.83	1.88	2.78	0.77	0.32	0.37	0.09	2.43	3.41	Moloney et al. (2022)
Silage/concentrate + sunflower/fish oil	8.34	2.14	2.65	0.74	0.34	0.37	0.10	2.43	3.28	
Barley based TMR + palmitic acid	–	0.42	3.42	0.46	0.10	0.36	0.06	0.98	4.46	Hennessy et al. (2021)
Barley based TMR + *n*-3 rumen protected supplement	–	0.56	4.07	0.53	1.60	0.77	0.55	3.45	4.95	
Grass hay + flaxseed	–	0.64	3.72	1.09	0.21	0.34	0.02	1.66	4.94	Mapiye et al. (2013)
Grass hay + sunflower seed	–	0.76	4.47	0.49	0.10	0.24	0.02	0.85	5.85	
Red clover silage + flaxseed	–	0.67	3.73	1.38	0.26	0.36	0.03	2.03	4.96	
Red clover silage + sunflower seed	–	0.79	5.17	0.39	0.10	0.23	0.02	0.74	6.89	
TMR	0.77	0.35	1.89	0.34	0.02	0.10	0.02	0.48	–	He et al. (2013)
TMR + 15% camelina meal	0.87	0.35	2.14	0.41	0.03	0.11	0.02	0.56	–	
TMR + 30% camelina meal	1.41	0.4	2.37	0.45	0.05	0.13	0.02	0.65	–	
Concentrate + rumen protected saturated fat	2.85	0.82	3.45	0.50	0.07	0.20	0.04	0.87	4.31	Noci et al. (2011)
Concentrate + camelina oil	4.61	0.95	2.86	1.27	0.11	0.20	0.05	1.75	3.70	
Concentrate + linseed oil	5.28	0.98	3.01	1.74	0.12	0.21	0.03	2.18	3.72	

TVA, trans-vaccenic acid; RA, rumenic acid; LA, linoleic acid; ALA, linolenic acid; EPA, eicosapentaenoic acid; DPA, docosapentaenoic acid; DHA, docosaehexanoic acid; n-3, omega-3 fatty acids; n-6, omega-6 fatty acids.

TMR, total mixed ration.

ALA, EPA and DPA, but lower undesirable SFA (C14:0, C16:0, C16:1) and *n-6:n-3* ratio compared with lamb and beef. Table 4 compares the fatty acid composition of chevon, lamb and beef determined from goat kids, lambs and calves, on % of total fatty acids.

Various factors affect the FA composition of goat meat, particularly the diet of the animal. Meat from goats grazing rangeland forages (Liotta et al., 2020) or high-forage diets supplemented with *n*-3 PUFA sources contain increased contents of *n*-3 PUFA and the BHIs than those raised intensively on high grain diets (Gagaoua et al., 2023). It has been reported that feeding goats with a grain diet containing threefold C18:1 compared to an alfalfa hay diet increased C18:1 in both IMF (i.e., marbling) and subcutaneous fat. Thus, when East African goats were supplemented with a grain diet (27% sunflower seed cake + 70% maize bran), the proportions of C18:1, TVA and LA in the omental fat increased compared to non-supplemented goats (Gagaoua et al., 2023). The increase in C18:1 in muscle or adipose tissues in response to higher grain levels in the diet could be due to the increase in the Δ9 desaturase enzyme activities necessary for the conversion of C18:0 to C18:1, which can also be seen in sheep and cattle.

When goats are fed with oils rich in LA, it can bypass the rumen or is isomerised to RA, which can be bio-hydrogenated to TVA in the rumen increasing their deposition in the muscle tissues. Supplementing goat diets with canola or olive oils (e.g., oils rich in oleic acid) and sunflower or soybean oils (e.g., oils rich in LA) has mainly resulted in an increase in C18:1 and RA in the meat, respectively. On the other hand, supplementation of diets with oils rich in ALA can lead to an increase in the *n*-3 FA level in chevon. Related to this, the incorporation of 3% canola oil, a good source of ALA with a 2:1 ratio of n-6:n-3, into the goats' diet has enhanced ALA in the muscle, liver, and kidney fats (Karami et al., 2013). Studies report that supplementation of diets with oils can affect expression levels of genes associated with *de novo* FA synthesis in goats. A blend of linseed and palm oils (2:1) has reduced both rumen biohydrogenation of ALA and muscle oxidation of ALA in Cashmere goats. Diets supplemented with the blended oil, compared to linseed alone, have reduced the relative abundance of *Pseudobutyrivibrio*, a bacterial species that hydrogenate dietary ALA in the rumen, increasing *n*-3 PUFA, leading to a decrease in the *n*-6:*n*-3 FA ratio in goat meat. In this regard, a variety of nutritional strategies have been employed to

TABLE 4 Comparison of fatty acid composition (% of total fatty acids) and intramuscular fat (IMF, g per 100 g of meat) of muscle *longissimus dorsi* from goats (kids), lambs and calves.

Fatty acids	Goat kids	Lambs	Calves	SEM	P-value
Lauric acid (C12:0)	0.32	0.35	0.17	0.11	0.50
Myristic acid (C14:0)	1.77^{b}	2.62^{ab}	3.22^{a}	0.27	<0.01
Palmitic acid (C16:0)	20.0^{b}	23.5^{a}	26.0^{a}	0.78	<0.01
Unhealthy fatty acids (C14:0+C16:0+C16:1)	24.0^{b}	27.6^{b}	32.4^{a}	1.22	<0.01
Stearic acid (C18:0)	17.7	16.9	16.1	1.22	0.66
Saturated fatty acids (SFA)	41.4^{b}	46.2^{a}	47.4^{a}	1.35	0.02
Myristoleic acid (C14:1 *n*-9)	0.11^{b}	0.69^{a}	0.05^{b}	0.11	<0.01
Palmiteoleic (C16:1 *n*-9)	2.30^{ab}	1.51^{b}	3.10^{a}	0.40	0.05
Palmiteoleic (C17:1 *n*-9)	0.63	0.76	0.91	0.25	0.73
Oleic acid (C18:1 *n*-9)	39.8^{a}	39.8^{a}	35.1^{b}	1.38	0.01
Linoleic acid (LA; C18:2 *n*-6)	4.55	5.10	6.53	0.87	0.28
α-Linolenic acid (ALA; C18:3 *n*-3)	1.81^{a}	0.78^{b}	0.69^{b}	0.16	<0.01
Arachidonic acid (AA; C20:4 *n*-6)	2.04	1.82	1.63	0.44	0.81
Eicosapentaenoic acid (EPA; C20:5 *n*-3)	1.37^{a}	0.41^{b}	0.25^{b}	0.18	<0.01
Docosapentaenoic acid (DPA; C22:5 *n*-3)	1.44^{a}	0.49^{b}	0.56^{b}	0.19	<0.01
Docosahexaenoic acid (DHA; C22:6 *n*-3)	0.26	0.24	0.10	0.08	0.27
Sum of *n*-6 fatty acids	7.54	7.15	8.87	1.26	0.60
Sum of *n*-3 fatty acids	5.12^{a}	1.96^{b}	1.60^{b}	0.49	<0.01
PUFA/SFA ratio	0.33	0.21	0.24	0.04	0.20
n-6/*n*-3 ratio	1.53^{c}	3.52^{b}	6.04^{a}	0.42	<0.01
Intramuscular fat content (g per 100 g meat)	2.6^{b}	3.9^{a}	2.7^{b}	0.37	<0.01

Source: Kiani et al. (2017); Values are average of 10 observations (n = 10); SEM, Standard error of means; PUFA, polyunsaturated fatty acids.
^{a,b,c,}mean values within a row with different superscript letters are significantly different (P<0.05).

increase HEFA deposition in goat meat, which have been summarised in Table 5.

3 Feed-based enrichment of antioxidants in red meat from sheep, cattle and goats

It is known that diets rich in antioxidants offer better animal health (Ponnampalam et al., 2022), including resistance to heat stress and contribute to a reduction in deteriorative changes in meat quality post mortem by reducing radical formation within the cellular system and reducing the amount of oxidative damage in muscle tissues (Bekhit et al., 2013; Karre et al., 2013; Ponnampalam et al., 2022). Antioxidants reduce the occurrence of oxidative stress and infectious diseases in animals and humans (Lauridsen, 2019; Ponnampalam et al., 2022). Vitamin E (primarily α-tocopherol) is considered an efficient antioxidant functioning compound in a hydrophobic environment. It has been proven from animal and human studies that vitamin E inhibits lipid peroxidation (Gruffat et al., 2020), and by scavenging lipid peroxyl radicals, it prevents or delays the propagation of free radical-mediated chain reactions in the cellular systems. Antioxidants can act synergistically, for example, α-tocopherol and β-carotene can act as an effective 'radical-scavenging mechanism' in biological membranes (Kurutas, 2015; Salami et al., 2016; Lauridsen et al., 2021). The inhibition of lipid peroxidation by a combination of the two fat-soluble antioxidants was shown to be greater than the sum of the individual inhibitions (Wrona et al., 2003). Figure 3 illustrates the mechanism of the effect of antioxidants on the quality of meat from ruminant animals (goat is taken as an example in the diagram). The antioxidant action of vitamin E and selenium have been proven in human and animal studies by their fortification in the tissues and defensive effects to reduce oxidation (Nozière et al., 2006). Carotenoids are also regarded as efficient O_2 and ROS scavengers operating in cellular lipid bilayers. However, the action of other plant-based antioxidants, namely polyphenols (phenolic acids, tannins, flavonoids), has not been proven through their fortification in animal or human tissues. Flavonoids are thought to have a lower contribution to the direct antioxidative protection in animals and humans, due to their relatively poor absorption and difficulties with storage in animal tissues, even though they are potent scavengers of hydroxyl and superoxide radicals (Fiedor and Burda, 2014).

3.1 Influence of diets on antioxidants in lamb and mutton

Modulating the FA profile of lamb and mutton to increase beneficial PUFAs increases susceptibility to lipid oxidation, which can negatively affect meat quality attributes. The presence of natural or supplemented antioxidants in the diet of ruminants can help to reduce oxidation and increase shelf-life (Prache et al., 2022b). Meat from pasture-fed sheep and lambs is characterised by having higher muscle antioxidants levels (mainly α-tocopherol) compared to those fed grains (Zervas and Tsiplakou, 2011; Gruffat et al., 2020), as fresh pasture is a rich source of antioxidants such as tocopherols, carotenoids and phenolic compounds (Prache et al., 2022b). However, variability between breeds in the metabolic fate of ingested carotenoids has been observed (Macari et al., 2017). The presence of different plant species within the pasture can also modulate antioxidant contents in meat, with higher α-tocopherol concentrations reported in the meat of lambs grazing brassica and lucerne/phalaris compared to bladder clover (De Brito et al., 2017). Leguminous species are reported to contain lower levels of α-tocopherol compared to grasses, which may explain higher lipid oxidation values in the meat of lambs grazing alfalfa versus perennial ryegrass (Fraser et al., 2004), however variable results have been reported (Hampel et al., 2021).

The antioxidant content of lamb meat declines with increased inclusion of senesced pasture and TMR in the diet (Ponnampalam et al., 2012, 2017), due to the lower levels of tocopherols, carotenoids and phenolic compounds available in these feed types (Moure et al., 2001). Supplementing feedstuffs containing natural antioxidants to increase concentrations in meat has yielded variable results (Falowo et al., 2014). Supplementing TMR diets with pomegranate silage (Kotsampasi et al., 2014), buckwheat silage (Keles et al., 2018) and increasing levels of Acacia mearnsii leaf-meal (Uushona et al., 2023) increased the antioxidant capacity and phenolic content of lamb meat. Inclusion of oat grain in senesced perennial ryegrass pasture lowered α-tocopherol concentrations in lamb meat compared to senesced perennial lucerne pasture. A reduction in α-tocopherol concentrations and increasing oxidation values have been reported in meat from lambs fed TMR supplemented with algae (Hopkins et al., 2014; Ponnampalam et al., 2016) and camelina hay/meal (Ponnampalam et al., 2021a). Overall, pasture grazing is the most advantageous way to increase the antioxidant content of sheep and lamb meat. Supplementation of senesced pasture and TMR diets with antioxidant rich by-products is important to sufficiently improve the antioxidant content of meat.

3.2 Influence of diets on antioxidants in beef and veal

Use of dietary antioxidants is the most common strategy used to inhibit lipid, protein, and myoglobin oxidation in beef (Estévez, 2021; Petcu et al., 2023) and veal (Skřivanová et al., 2007; D'Agata et al., 2009). It has long been established that forage-based versus grain-based diets are highly endowed with diverse and potent antioxidants, which result in beef and veal with superior antioxidant and oxidative stability profiles (Descalzo and Sancho, 2008; Estévez, 2021). For illustrative purposes, feeding pasture versus grain diets can increase vitamin E content in beef up to 5.9 μg/g of tissue exceeding the ideal concentration of 3.3-3.8 mg/g tissue required to extend oxidative shelf life of beef (Liu et al., 1995; Descalzo and Sancho, 2008). However, the efficacy of these antioxidants in pasture-fed beef depends on dose and type of the antioxidant, plant species and maturity, seasonality, physical form,

TABLE 5 Influence of diet on the health enhancing fatty acid composition (% of total fatty acids) of meat from goats.

Diet	Fatty acids (%)									Reference
	TVA	RA	LA	ALA	EPA	DPA	DHA	*n*-3	*n*-6	
Forage vs. concentrate										
Rangeland pasture	–	0.13	–	–	–	–	–	0.12	0.18	Ryan et al. (2007)
Rangeland + 50% concentrate	–	0.15	–	–	–	–	–	0.05	0.21	
Rangeland + 70% concentrate	–	0.21	–	–	–	–	–	0.04	0.28	
Rangeland + 90% concentrate	–	0.36	–	–	–	–	–	0.00	0.02	
Oil supplementation										
Palm oil diet	–	–	0.54	1.39	1.12	–	0.86	4.17	8.71	Wang et al. (2020)
Linseed oil diet	–	–	0.64	1.52	1.22	–	1.04	4.69	9.65	
Mixed oil diet	–	–	0.51	1.71	1.51	–	1.25	5.44	8.91	
TMR	1.22	0.55	8.88	0.51	0.37	0.29	0.37	1.47	12.75	Abuelfatah et al. (2016)
TMR + 10% whole linseed	0.96	0.73	4.85	2.32	0.79	0.60	0.63	4.34	7.06	
TMR + 20% whole linseed	1.28	0.53	4.85	3.33	1.23	1.08	1.08	6.30	7.34	
TMR + canola oil	2.71	0.86	9.81	1.61	1.33	1.96	1.38	6.12	16.1	Karami et al. (2013)
TMR + palm oil	1.23	0.61	9.93	1.12	1.17	1.48	1.23	4.61	15.7	
TMR + palm oil	–	–	3.78	0.42	0.18	–	0.16	0.76	4.41	Najafi et al. (2012)
TMR + soybean oil	–	–	5.26	0.7	0.19	–	0.19	1.09	5.87	
TMR + fish oil	–	–	3.59	0.47	0.6	–	0.57	1.65	3.93	
By-products										
TMR	1.75	0.14	4.43	3.99	0.33	0.11	–	4.43	5.84	Semwogerere et al. (2023)
TMR + 5% hemp seed cake	3.12	0.18	4.84	5.38	0.44	0.15	–	5.92	6.78	
TMR + 10% hemp seed cake	3.79	0.19	4.9	6.08	0.52	0.19	–	6.79	7.33	
TMR	0.44	3.33	0.46	2.50	0.99	0.24	–	3.78	4.85	Kafle et al. (2021)
TMR + 25% peanut skin	0.37	3.48	0.42	2.72	0.96	0.24	–	3.92	4.93	
TMR + 50% peanut skin	0.38	3.73	0.49	2.80	0.88	0.24	–	3.92	5.22	
TMR + 75% peanut skin	0.36	3.42	0.41	2.33	0.99	0.24	–	3.56	4.89	
TMR	1.19	0.51	3.19	0.34	–	0.46	–	0.62	6.19	Martins Flores et al. (2021)
TMR + 50% grape pomace silage	1.51	0.49	4.89	0.37	–	0.30	–	0.62	8.15	
TMR + 50% grape pomace silage	2.33	0.68	5.71	0.41	–	0.21	–	0.62	10.63	
TMR + 50% grape pomace silage	4.17	1.03	7.03	0.43	–	0.24	–	0.79	13.99	
TMR	1.56	–	4.70	0.43	0.2	0.39	0.04	0.47	5.85	Pimentel et al. (2021)
TMR + 16 kg *Acacia mearnsii* extract	1.84	–	4.72	0.41	0.22	0.46	0.04	0.54	7.49	
TMR + 32 kg *Acacia mearnsii* extract	1.60	–	5.46	0.47	0.16	0.35	0.04	0.47	4.93	
TMR + 48 kg *Acacia mearnsii* extract	1.52	–	7.62	0.72	0.22	0.62	0.05	0.61	9.56	
TMR	0.47	–	12.36	0.6	0.39	0.56	0.41	1.95	18.32	Abubakr et al. (2015)
80% decanter cake	0.33	–	9.38	0.63	0.32	0.63	0.32	1.89	14.51	
80% palm kernel cake	0.40	–	9.14	0.61	0.32	0.58	0.36	1.89	14.16	
TMR + 5% palm oil	0.41	–	9.04	0.69	0.39	0.62	0.36	2.06	14.02	
TMR	–	–	8.01	1.06	0.33	–	–	1.39	11.8	Ahmed et al. (2015)

(Continued)

TABLE 5 Continued

Diet	Fatty acids (%)									Reference
	TVA	RA	LA	ALA	EPA	DPA	DHA	*n*-3	*n*-6	
By-products										
TMR + 0.5% green tea by-product	–	–	14.2	1.06	0.16	–	–	1.22	17.1	
TMR + 1% green tea by-product	–	–	13.1	1.03	0.29	–	–	1.32	17.5	
TMR + 2% green tea by-product	–	–	16.4	1.51	0.15	–	–	1.66	21.1	

TVA, trans-vaccenic acid; RA, rumenic acid; LA, linoleic acid; ALA, linolenic acid; EPA, eicosapentaenoic acid; DPA, docosapentaenoic acid; DHA, docosaehexanoic acid; n-3, omega-3 fatty acids; n-6, omega-6 fatty acids.
TMR, total mixed ration.

duration of feeding, amount, and type of pro-oxidants (Ponnampalam et al., 2022; Kearns et al., 2023b).

Low-quality forages and high-grain diets can be supplemented with vitamin E to elevate levels in beef (Descalzo and Sancho, 2008; Petcu et al., 2023) and veal (D'Agata et al., 2009; Franco et al., 2012), subsequently minimizing oxidative deterioration. It has been suggested that vitamin E daily supplementation of 500 IU/head for 126 d or 1300 IU/head for 44 d could meet the ideal vitamin E levels in muscle required to enhance oxidative stability of beef (Liu et al., 1995; Suman et al., 2014). Apart from vitamin E, supplementation of organic selenium appears to somewhat increase oxidative capacity and stability of beef (Rossi et al., 2015; Huang et al., 2023) and veal (Skřivanová et al., 2007; Shabtay et al., 2008). In addition, supplementation of high-grain diets with polyphenolic extracts including flavonoids (Orzuna-Orzuna et al., 2023), a blend of alkaloids, saponins, and phenolic acids (De Zawadzki et al., 2017), resveratrol (Cui et al., 2023), ferulic acid (González-Ríos et al., 2016) and tannic acid (Tabke et al., 2017) enhances the antioxidant capacity and oxidative stability of beef. Similarly, supplementation of polyphenolic fruit by-products such as grape pomace in calves' (Ianni et al., 2019) and steers' (Tayengwa et al., 2020) on high-grain diets increased the antioxidant capacity and oxidative stability of meat. Supplementing a blend of essential oils (Rivaroli et al., 2016; Ornaghi et al., 2020) and benzoic acid (Williams et al., 2022) slightly improved lipid stability without affecting colour shelf-life.

The effect of distiller's grains on the oxidative capacity and lipid stability of beef varies from negative (Suman et al., 2014; De Mello et al., 2018) to neutral (Gill et al., 2008; Depenbusch et al., 2009) and positive (Bloomberg et al., 2011; Merayo et al., 2022) and, thus, merits further investigation. Interestingly, a blend of antioxidant sources tends to either have additive or synergistic effects. For example, a combination of vitamin E with polyphenolic extracts (Gobert et al., 2010; Delosière et al., 2020), essential oils (Fusaro et al., 2021) and distiller's grains (Bloomberg et al., 2011) was more efficient in increasing antioxidant capacity and oxidative stability than the individual constituents, suggesting synergistic effects with vitamin E. However, high dietary levels of vitamin A suppress tissue deposition of vitamin E reducing antioxidant capacity and oxidative stability of beef (Daniel et al., 2009; Marti et al., 2011). Research should continue to explore synergistic effects of novel nutrient and non-nutrient antioxidants.

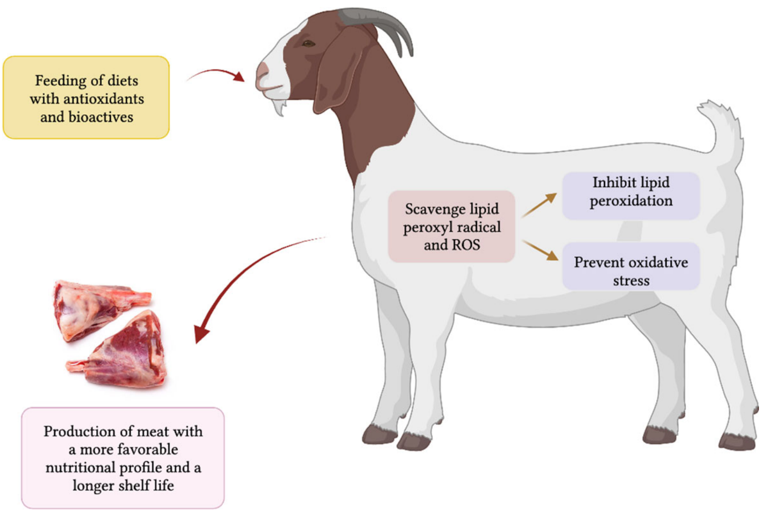

FIGURE 3
Mechanism of the effect of antioxidants (vitamins and carotenoids) and bioactives enriched feed on the animal health and meat quality of sheep, cattle and goats (goat is taken as an example).

3.3 Influence of diets on antioxidants in chevon

Pasture-finished goats differ in colour attributes of meat (L*, a, b, chroma and hue angle values) than goats finished on grain diets (Lee et al., 2008), the same for meat from sheep and cattle. Adding natural antioxidants (Vitamin E, Vitamin C, etc.) and polyphenols, as a nutritional strategy influences the colour stability of goat meat (Karami et al., 2011). For example, pomegranate seed pulp, a cheap source of polyphenols, has improved colour stability in chevon (Emami et al., 2015). Similarly, a dietary green tea by-product (20 g/kg dry matter) has improved the redness and yellowness values of goat meat (Ahmed et al., 2015).

It is noteworthy that supplementing the diet with a high content of *n*-3 PUFA might increase lipid oxidation and may raise concerns about the impairment of sensory attributes of chevon, similar to that observed with beef and lamb. The inclusion of high doses of *n*-3 PUFA has produced meat with unusual odours, unpleasant flavours, and a lower overall appreciation of kid meat (Moreno-Indias et al., 2012). A positive association between lipid oxidation and the content of *n*-3 PUFA in chevon has been reported (Abuelfatah et al., 2016). Intriguingly, liver and muscle (meat) fats from canola oil-fed kids contained fewer lipid oxidative substances compared to those from palm oil-supplemented kids (Karami et al., 2013). The latter study showed that canola oil effectively reduced lipid oxidation both in the blood and muscle tissue of goats. Furthermore, the concern about lipid oxidation of high-PUFA diets could be overcome by dietary supplementation of antioxidant polyphenols, a conclusion that is relevant to all ruminant species.

It has been reported that supplementation of diets containing polyphenols positively improved the FA profile and reduced lipid oxidation in chevon (Cimmino et al., 2018). Similarly, dietary green tea by-products (Ahmed et al., 2015) and extracts from olive mill water waste (Cimmino et al., 2018) reduced lipid oxidation in chevon. Overall, it seems that diets containing phenolic components are positive agents in reducing lipid oxidation in goat meat. These actions may be through synchronised effects with lipids such as unsaturated fatty acids and vitamins (such as vitamin E) at the GIT enterocyte level. However, the dietary biofortification of phytonutrients into tissues such as skeletal muscles is low due to lower rates of digestion and absorption; this is believed to be due to their action as antinutritional factors (causing toxicity to microbes) or binding agents with other nutrients (e.g., protein) leading to complex formation at the GIT level, resulting in reduced microbial degradation.

4 Future directions and gaps

The importance of HEFA and antioxidants is becoming increasingly important, particularly in relation to animal health, as well as the quality and nutritional value of meat, and ultimately human health and wellbeing. Also, there is an increasing trend towards the consumption of red meat compared with other white meats around the world, as global population and affluency increase mainly from Asian and African regions. The social awareness of consumers relating to the quality of meat consumed, the nutrient content of meat that they select, and the health aspects of foods chosen is also expected to change in the coming years as world population become aware of healthy living (Ponnampalam and Holman, 2022). Therefore, addressing the enrichment of red meat with HEFA and antioxidants i.e., improving the nutritional value of meat, has gained much attention. The use of bioactive-rich (vitamins, HEFA, phenolic compounds, tannins, flavonoids) plant by-products for improving the nutritional quality attributes and shelf-life of the meat is under active investigation (Salami et al., 2019), but research is needed to evaluate their effects on other meat quality attributes and animal performance. A point of caution is meat safety, insofar as certain pathogenic agents in plants can be transferred to the meat (Prache et al., 2022a). Although several studies have investigated the effects of feed on the quality and nutritional values of meat, there is a lack of information on the absorption and bioavailability of particular feed-based antioxidants and FA, and their effect in animal- and human-tissues upon deposition. Some authors also point to the gap between food-scale studies and epidemiological studies (Prache et al., 2022a). There is a lack of data linking the FA profile of meat and its antioxidant content (and more generally the way it is produced), to the level of consumption and chronic diseases in humans. This requires a collective effort between research communities working in animal science, meat processing, consumer attitudes, human nutrition and epidemiology (Prache et al., 2022a).

Comparative studies on the consumption of red meat from ruminants versus white meat and their combinations as well as comparing with other sources of animal and plant proteins can provide valuable insights and knowledge into their potential effects on human health. However, this research aspect is lacking and not well proven by human intervention studies, relating it to long term consumption of red meat enriched with HEFA and antioxidants on blood lipid parameters, human health and wellbeing. This may be due to inadequate funding allocated by government bodies around the globe as it requires large funding and intense resources, as well as due to the ethical considerations, regulatory requirements, and recruitment challenges in enrolling adequate numbers of participants (observations) to validate data. Future studies should focus on not only investigating the absorption, bioaccessibility, and bioavailability of different antioxidants and FA through use of *in vitro* digestion models and *in vivo* animal studies, but also include human intervention studies undertaken with sound experimental designs covering appropriate replicates and number of observations, comparing the effects of red meat, white meat and other plant and animal protein sources (alone and/or in combination) in human health. Furthermore, animal and human cell lines should be treated (fortified) with plant-based antioxidants, for example phenolic acids or flavonoids, to study their real effects in animal and human tissues as they show antinutritional activities that may lead to lower digestion, absorption and biofortification. Such studies may provide an understanding of the impact of phytonutrients acting as a sole or additive components along with HEFA and other antioxidants (vitamin E, selenium) that are available in the meat to exert a beneficial effect on humans. This, in turn, is key to gaining a deep insight into the mechanism of action of improving human health via enriching red meat with feed-based FA and antioxidants.

5 Conclusions

Regardless of ruminant species, high-quality pasture remains superior in producing meat enriched with HEFA, particularly *n*-3 PUFA and antioxidants, with some countries already utilising 'grass-fed' logos (see Salami et al., 2019; Davis et al., 2022). Low-quality forages and high grain diets require dietary supplementation with *n*-3 PUFA and antioxidants to raise their contents in meat and extend its shelf life. The importance of some dietary vitamins and minerals in the antioxidant actions and preservative aspects of PUFA in meat has been documented. A combination of nutrient antioxidants, mostly vitamin E and non-nutrient antioxidants, chiefly flavonoids, and carotenoids are speculated to synergistically stabilise high PUFA contents in ruminant meat. Nevertheless, the latter statement needs validation through well-designed *in vivo* studies undertaken in animal and human populations (with adequate replicates and numbers of observations) along with the quantification of flavonoids or carotenoids in circulatory systems and tissues such as skeletal muscles, and consequently their effects on human health. To this end, research should continue to explore effects of co-feeding of PUFA sources with different mixtures of novel nutrient and non-nutrient antioxidants on animal and human health as well as the underlying mechanisms.

Author contributions

EP: Conceptualization, Writing – original draft, Writing – review & editing. MK: Writing – original draft, Writing – review & editing. AK: Writing – original draft, Writing – review & editing. SS: Writing – original draft, Writing – review & editing. PV: Writing – original draft, Writing – review & editing. SP: Writing – original draft, Writing – review & editing. FM: Writing – original draft, Writing – review & editing. CM: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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