Food Chemistry: X 25 (2025) 102159

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x

Effects of intramuscular fat on the flavor of fresh sheep and goat meat: Recent insights into pre-mortem and post-mortem factors

Tianyu Su[a,1], Yu Fu[b,1], Jingjie Tan[a], Mohammed Gagaoua[c], Kathrine H. Bak[d], Olugbenga P. Soladoye[e], Zhongquan Zhao[a], Yongju Zhao[a], Wei Wu[a,*]

[a] College of Animal Science and Technology, Southwest University; Chongqing Key Laboratory of Herbivore Science, Chongqing 400715, China
[b] College of Food Science, Southwest University, Chongqing 400715, China
[c] Pegase, Inrae, Institut Agro, 35590, Saint-Gilles, France
[d] FFoQSI - Austrian Competence Centre for Feed and Food Quality, Safety and Innovation, FH OÖ Campus Wels, Stelzhamerstraße 23, A-4600 Wels, Austria
[e] Agriculture and Agri-Food Canada, Government of Canada, Lacombe Research and Development Centre, 6000 C&E Trail, Lacombe, Alberta T4L 1W1, Canada

ARTICLE INFO

Keywords:
Marbling
Odor
Sheep meat
Goat meat
Farm-to-fork factors

ABSTRACT

Sheep and goat meat products are becoming increasingly popular among consumers due to their unique flavor derived from intramuscular fat (IMF), which contributes to formation of the distinctive odor. However, there is currently a dearth of reviews on the impact of IMF on the flavor of sheep and goat meat. The present review aims to discuss the relationships between IMF and flavor through lipid composition and fatty acid (FA) distribution, provide an overview of characteristic flavor compounds affecting the flavor of sheep and goat meat, and shed light on the impacts of pre-mortem and post-mortem factors on meat flavor attributed to changes in FAs and flavor compounds. Controlling pre-mortem practices and adjusting post-mortem harvesting methods are key factors in shaping and/or driving the flavor of sheep and goat meat products. This review enhances the comprehensive understanding of the impact of IMF on the flavor of sheep and goat meat.

1. Introduction

According to the statistics, the global production of goat and sheep meat has witnessed a remarkable surge of 161.4 %, soaring from 6.03 million tons to 15.77 million tons (Wang, 2023). This is attributed to the appreciable nutritional properties and distinctive flavor of sheep and goat meat, although goat meat is less popular compared to sheep meat (Qi et al., 2023). The presence of unpleasant odor is more pronounced in goat meat than in sheep meat, and the unpleasant odors are more prominent in cooked meat of older goats and sheep, primarily influenced by intramuscular fat (IMF) content and fatty acid (FA) composition, which is considered unacceptable by some consumers (Teixeira et al., 2020). Hence, understanding the relationship between IMF and flavor of sheep and goat meat is crucial. IMF plays a crucial role in shaping the inherent qualities of sheep and goat meat (Listrat et al., 2016). The content of IMF typically ranges from 1 % to 6 % and directly influences consumer preferences for sheep and goat meat (Li et al., 2020; Zhang et al., 2024). A recent study has revealed that there is a high overall consumer preference for New Zealand fattened lamb (approximately 3 % IMF), with the highest consumer ratings being achieved at 4 % IMF (Realini, Pavan, Johnson, et al., 2021; Realini, Pavan, Purchas, et al., 2021). However, a recent study has shown that an increase in IMF% from 1.5 % to 5.5 % in lambs can result in a rise in the content of trans-fatty acids and BCFA (Realini, Pavan, Johnson, et al., 2021; Realini, Pavan, Purchas, et al., 2021). Therefore, it is important to control the range of the increased IMF content. This approach can stimulate consuming behavior and health benefits. However, the changes in IMF might lead to alterations in lipid composition, which affects the consumer liking of sheep and goat meat (Pavan, Subbaraj, et al., 2022). This phenomenon can be partly related to polyunsaturated fatty acids (PUFA) in triglycerides (TG) and phospholipids (PL) that contribute to different flavor intensities (Pavan, Subbaraj, et al., 2022). It has been shown that a high content of IMF can increase the content of volatiles compounds, whereas a lower IMF content hinders the dispersion of these volatiles (Bravo-Lamas et al., 2018; Li et al., 2022).

The flavor in sheep and goat meat is mainly divided into taste and aroma, the formation of which is very complex and can be influenced by various factors, with IMF content, lipid composition, and content and

* Corresponding author.
E-mail address: weiwu2019@swu.edu.cn (W. Wu).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.fochx.2025.102159
Received 27 September 2024; Received in revised form 19 December 2024; Accepted 2 January 2025
Available online 4 January 2025

ratio of FAs being particularly relevant (Watkins et al., 2013). These factors are primarily determined by a range of pre-mortem interacting factors, such as feed type, feed management, species, breed, age, and sex. Among these factors, nutritional and feed management have been found to significantly impact the flavor of sheep and goat meat, as IMF content, lipid composition, and FA distribution are predominantly regulated via dietary pathways (Dou et al., 2023; Insausti et al., 2021; Zhang, Han, et al., 2022). For instance, augmenting the diet of Qianbei Ma goat with 1 g/d of purple corn pericarp (PCP) increased the contents of 1-hexanol and 1-octanol, thereby enriching goat meat with vegetal, herbaceous, fatty, and fruity flavor, when compared to the meat from a basal diet (Tian et al., 2021). Supplementation of 3 % *Perilla frutescens* seeds in the diet of Tan sheep increased the content of acetaldehyde and 1, 2, 4-trimethylbenzene in the meat and imparted a fruity flavor and violet aroma (Yu et al., 2024). The mechanisms by which nutritional factors influence muscle metabolism in relation with IMF and the flavor of sheep and goat meat may to some extent be related to the regulatory role of rumen microorganisms (Ma et al., 2023). However, the specific mechanism between rumen microorganisms and muscle metabolism is still unclear, and the impact of gene regulation may also be crucial (Li, Zhao, Jian, et al., 2023; Sha et al., 2023). Although pre-mortem factors play an important role in the regulation of flavor-related FAs, fresh sheep and goat meat possesses primarily a bloody and metallic aroma; however, the development of more complex aromas is predominantly achieved through thermal processing (Sohail et al., 2022). As a result, post-mortem factors, induced by thermal degradation during thermal processing, contribute to generating a significant number of volatile compounds and enhancing flavor. For example, when Tan lamb was subjected to electric roasting, the concentration of hexanal and 1-octen-3-ol, two compounds known for imparting grassy, mushroom, and earthy flavors, underwent a significant increase and reached their maximum levels within a roasting duration of 2–8 min (Wang, Luo, & Wang, 2022).

The influence of pre-mortem factors on the flavor of sheep and goat meat has been extensively investigated, whereas the impact of post-mortem factors on their flavor has received relatively less attention (Sha et al., 2023). Hence, the present work aims to review the recent progress in the contribution of IMF attributes to sheep and goat meat flavor quality. Also, the involved pre-mortem (e.g. diet, feed additives, feed management, species, breed, age, and sex) and post-mortem factors (e.g. aging, freezing, dry curing, fermentation, as well as packaging and thermal processing) were discussed.

2. Lipid composition and volatile compounds in sheep and goat meat

2.1. Effect of lipid composition on the flavor of sheep and goat meat

The PL and neutral lipids are the most important components of IMF, with a high proportion of PL (e.g., Phosphatidylcholine, PC; phosphatidylethanolamine, PE, etc.) in muscle and deposited as PUFA. PUFA are key lipids for production of volatile flavor compounds, while neutral lipids in muscle play an important role in the retention of volatile compounds (Hocquette et al., 2010; Liu, Hou, et al., 2022; Liu, Hui, et al., 2022; Liu, Li, et al., 2022). Changes in IMF content can lead to alterations in lipid distribution. It was found that TG and diglycerides (DG) were positively correlated with IMF content in the *Longissimus lumborum* (LL) muscle of Hu sheep, and that PL varied significantly with different levels of IMF (Li et al., 2022). This phenomenon resulted in differences in FA composition and flavor between these two groups. The components of PUFAs determined in goat meat were side chains bound to glycerophospholipids, glycerolipids, or sphingolipids rather than free FAs. Studies on irradiated goat meat by lipidomics revealed a significant increase in total TG, PC, PE, lyso-phosphatidylethanolamine (LPE), lysophosphatidylcholine (LPC), ceramide (Cer), sphingosine (Sph), which were associated with increases in goat meat flavor-related PUFAs, such as linoleic acid (LA) and α-linolenic acid (ALA) (Jia et al., 2021). Therefore, lipid categories and profiles in sheep and goat meat are important for meat products.

2.2. Effect of FA distribution on the flavor of sheep and goat meat

The increase in IMF resulted in changes in fatty acid content, which can affect the flavor of meat. When the IMF percentage of pasture-fed lambs increased from 1.5 % to 5.5 %, significant alterations in fatty acid (FA) content and composition were observed. Notably, there was an increase in branched-chain fatty acids (BCFAs) associated with undesirable flavors, as well as an increase in C18:2 cis-9, trans-11 (rumenic acid), which is linked to flavor enhancement (Realini, Pavan, Johnson, et al., 2021; Realini, Pavan, Purchas, et al., 2021).

The variations in FA distribution within IMF, particularly oleic acid (C18:1), CLA (C18:2), and linolenic acid (C18:3), are the main contributors to the alteration of the flavor of sheep and goat meat (Arshad et al., 2018; Aung et al., 2023). C18:1 and C18:2 are responsible for the production of most of the volatile compounds in meat following lipid oxidation. The major FA in grass-fed sheep is C18:3, associated with the high content of C18:3 in pasture, which is involved in the formation of meat flavor, mainly deposited as PL (Ponnampalam et al., 2024; Yang, Li, et al., 2022; Yang, Liu, et al., 2022).

The quality and flavor of meat were negatively impacted when the concentration of ALA in sheep meat approached 3 % of TG or PL (Wood et al., 2004). Moreover, both sheep and goat meat contain the flavor compound with an undesirable odor linked to lipids, specifically odd and branched-chain fatty acids (OBCFAs), along with stearic acid (C18:0) (Gunawan et al., 2018). Several studies have demonstrated that the increased IMF content is positively correlated with BCFA (Chang et al., 2024; Pavan, McCoard, et al., 2022; Pavan, Subbaraj, et al., 2022), while the content of BCFAs was higher in those exhibiting elevated IMF content. (Chang et al., 2024). Three specific compounds categorized as BCFAs, namely 4-methyloctanoic acid (MOA), 4-ethyl octanoic acid (EOA), and 4-methylnonanoic acid (MNA), played a predominant role in imparting the characteristic cooked "gamy" flavor (Watkins & Frank, 2019). To a lesser extent, it is also associated with C18:1, C18:2, and C18:3.

Complex interactions in the rumen allow changes in the aroma profile of sheep and goat meat. In addition to dietary sources, C18:0, a class of saturated fatty acid (SFA), can affect the flavor of meat by converting other FAs (C18:2, C18:1, and ALA) to C18:0 through microbial action in the rumen (Buccioni et al., 2012). Therefore, the olfactory profile of sheep and goat meat comprises a diverse array of fatty acids (FAs), notably C18:1, C18:2, and C18:3, which play a significant role in aroma generation. Additionally, the presence of OBCFA and C18:0 compounds significantly contribute to the undesirable odor observed in sheep and goat meat (Buccioni et al., 2012).

2.3. Characteristics of volatile compounds in sheep and goat meat

2.3.1. Types of volatile compounds

The flavor of sheep and goat meat is a sensory impression that is primarily divided into taste and aroma (Khan et al., 2015). Taste-active compounds are non-volatile and perceived through taste receptors, while aroma-active compounds are volatile and perceived through olfactory receptors (Bleicher et al., 2022). Lipid oxidation results in the generation of various volatile compounds, but their impact on aroma hinges on the concentration and odor threshold of these volatile compounds. Therefore, only a few aroma-active compounds play a substantial role in shaping the aroma of cooked meat (Sohail et al., 2022). Most volatile compounds with low odor thresholds contribute significantly to the aroma of sheep and goat meat. Certain aldehydes (e.g. hexanal, nonanal and 2-decenal) with potent aromas and low odor thresholds can contribute to the characteristic odors of sheep and goat meat (Arshad et al., 2018). However, when their concentrations exceed certain thresholds, they generate rancid or unpleasant odors (Calkins & Hodgen, 2007). For instance, (E)-2-nonenal, with the odor threshold of 0.08 ng/g, represents a primary determinant of the aroma profile in goat meat (Dou et al., 2023). While (E)-2-nonenal can impart a strong fatty scent, an excessive presence will lead to deterioration in meat flavor (Dou et al., 2023). Although alcohols have a relatively mild effect on the flavor of meat compared to aldehydes, their concurrent presence can markedly influence the overall meat flavor profile. It is noteworthy that unsaturated alcohols, characterized by lower odor thresholds in contrast with saturated alcohols, significantly contribute to the meat flavor (Zhang et al., 2020). Besides, it has been reported that ketones have low odor thresholds and are represented in both grain and pasture feeding systems (Liu, Hou, et al., 2022; Liu, Hui, et al., 2022; Liu, Li, et al., 2022). In contrast, volatile flavor compounds with high odor thresholds generally have a minimal effect on the flavor of sheep and goat meat. Linear, branched, and cyclic hydrocarbons present in substantial quantities in sheep and goat meat possess high odor thresholds, so their impact on the overall aroma of sheep and goat meat remains limited (Echegaray, Dominguez, Bodas, et al., 2021; Echegaray, Dominguez, Cadavez, et al., 2021). Echegaray, Dominguez, Bodas, et al., 2021; Echegaray, Dominguez, Cadavez, et al., 2021 indicated that 5-methyl-3-heptanone was found to be the most abundant ketone, but it had not been detected in previous research, mainly due to its high odor threshold and limited influence on the aroma of sheep and goat meat.

The final products of lipid oxidation (aldehydes, alcohols, ketones, furans, etc.) exhibit high volatility, playing a pivotal role in the formation of characteristic flavor across various meat products (Fu et al., 2022). The key lipid-derived flavor compounds identified by gas chromatography-olfactometry (GC-O), along with their flavor descriptions and thresholds, are depicted in Fig. 1. It can be seen that although some volatile flavor compounds have high odor thresholds, they can still exert an impact on meat flavor, which is mainly concentration-dependent and dependent on Relative odor activity value (ROAV).

2.3.2. *Key meat flavor compounds*

The key determinants of aroma in sheep and goat meat are primarily attributed to essential flavor compounds. ROAV has been proposed to express odor activity values as the relative concentrations of volatile compounds, indicating the contribution of a particular volatile compound to the overall aroma (Cha et al., 2024). Therefore, ROAV serves as a valuable metric for assessing the degree to which both key flavor compounds and individual volatile compounds contribute to the overall flavor profile. When the ROAV of a volatile compound exceeds 1, it indicates that this particular component serves as the primary distinctive flavor compound. When the ROAV falls within the range of 0.1 to 1, it indicates that the volatile compound can impact the overall flavor (Liu et al., 2008). In sheep and goat meat, aldehydes are the key flavor compounds, followed by alcohols and ketones. The key volatile compounds with ROAV >1 include nonanal, octanal, hexanal, heptanal, decanal, (E)-2-nonenal, (E)-2-octenal, (E)-2-decenal, dodecanal, 1-octen-3-ol, 2-octen-1-ol, and 2,3-octanedione (Dou et al., 2023; Tian et al., 2021). These primary flavor compounds exhibit distinct flavor profiles and are listed in Fig. 1. For instance, nonanal is characterized by the descriptors fresh, fatty, citrus, green, sweet melon, while (E)-2-nonenal contributes cucumber, fatty, green flavors. 1-Octen-3-ol is associated with mushroom, and 2, 3-octanedione contributes roasted beans and creamy flavors (Qi et al., 2022). While sheep and goat meat

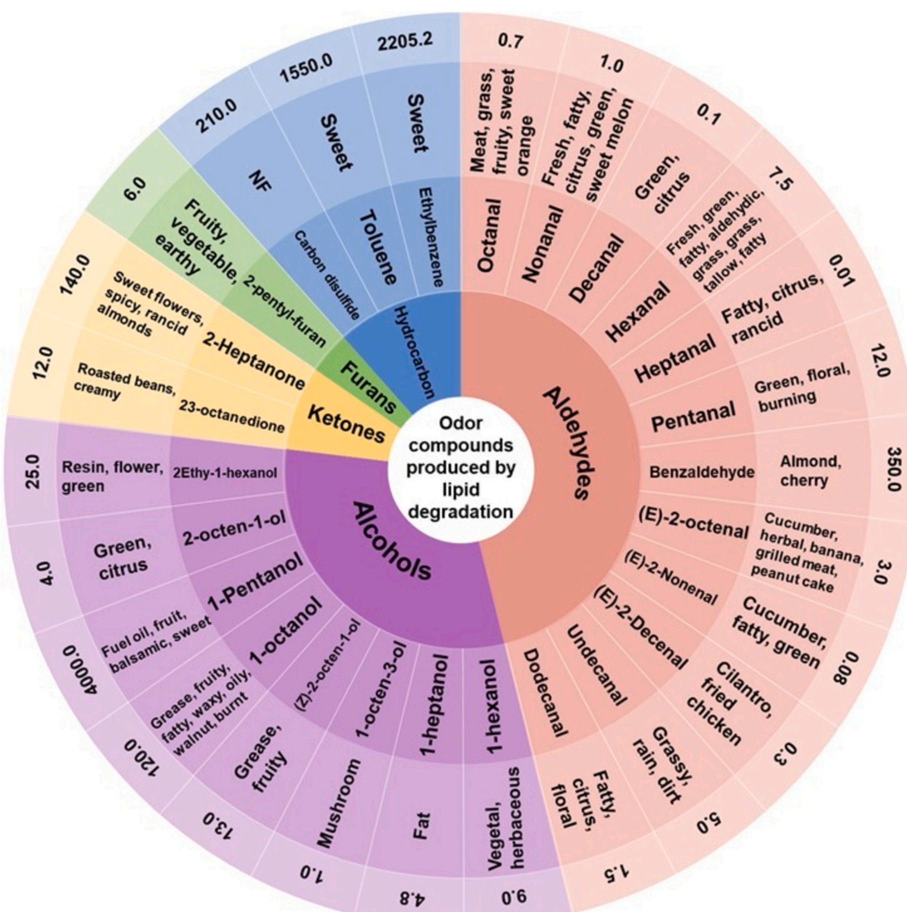

Fig. 1. A wheel of odor compounds produced by lipid oxidation that contribute to the odor of sheep and goat meat and the associated odor characteristics and threshold values (Unit, μg/kg or ng/g). Note: NF means not found. Formulated from Dou et al. (2023) with permission of MDPI publisher.

may share key flavor compounds, the flavor profiles of these compounds might exhibit slight variations due to differences related to the analytical methods and tools used to identify and quantify flavor compounds. For example, octanal typically imparts a fatty and green aroma, yet when goat meat is enriched with PCP in the diet, it can elicit a lemony odor (Tian et al., 2021). Furthermore, it has been observed that sheep grazing on pastures and receiving probiotic supplements may develop citrus-like and nutty flavor profiles (Liu, Hou, et al., 2022; Liu, Hui, et al., 2022; Liu, Li, et al., 2022). Volatile compounds with ROAVs ranging from 0.1 to 1 exhibit a modifying influence on the aroma of sheep and goat meat. For example, pentanal (ROAV = 0.64) was described as green, floral, and burning, and undecanal (ROAV = 0.93) was described as grassy, rain, and dirt (Liu, Hou, et al., 2022; Liu, Hui, et al., 2022; Liu, Li, et al., 2022). 1-Octanol (flatland grazing: ROAV = 0.452; mountain grazing: ROAV = 0.435) was described as fatty, waxy, walnut, and burnt, and (Z)-2-octen-1-ol (1 g/d PCP: ROAV = 0.274) was described as providing greasy and fruity notes (Dou et al., 2023; Tian et al., 2021). Similarly, 2-pentylfuran (0.5 g/d PCP: ROAV = 0.998) is noted for its fruity aroma. All these volatile compounds contribute to the flavor of sheep and goat meat, exerting their modifying effects.

3. Pre-mortem factors affecting IMF and volatile compounds in sheep and goat meat

Alterations in IMF content and volatile compounds constitute the primary determinants influencing the flavor profile in sheep and goat meat. Modifications in flavor primarily hinge upon non-genetic factors (including nutrition, age, sex, anatomical location, carcass weight, and weaning status) and genetic factors (e.g. breed and species) within the pre-mortem stage. This review emphasizes meat quality determinants based on their observability and controllability. Feed type and feed management, as controllable determinants, significantly impact livestock traits and meat quality. For instance, rearing environment and diet reveal nutritional status of livestock, fostering muscle development and fat deposition (Zhang, Han, Hou, Raza, Gui, et al., 2022b). Genetic factors also exert an impact on IMF and FA related meat quality traits (esp. tenderness and flavor). For example, breeding programs can be developed to screen for genes associated with these traits, although this process can be relatively time-consuming (Halli et al., 2022). For the time being, non-genetic factors are more applicable to production.

3.1. Different feeds

Energy feeds, silage feed, and plant by-products significantly influence IMF deposition, FA synthesis and formation of volatile compounds in sheep and goats. These changes subsequently impact the flavor of sheep and goat meat in distinctive manners. Several recent studies in this field are summarized in Table 1.

3.1.1. Energy feeds

The shifts in flavor profiles of sheep and goat meat attributable to energy-dense diets are primarily correlated with alterations in IMF deposition levels (Zhang, Yuan, et al., 2022). Also, fluctuations in volatile compound formation are also governed by rumen microbes. For instance, in the case of black Tibetan sheep fed a high-energy diet (HS), HS impacted volatile compounds by increasing the abundance of four key ruminal bacterial species. These microbial adjustments subsequently influenced multiple metabolic routes, impacting the biosynthesis of volatile compounds. As proposed in hypothetical Pathway 3 in Fig. 2, HS elevates ruminal microbial abundance and accelerates carbohydrate catabolism, thereby indirectly modulating FAs and volatile compound levels. Pathways 1 and 2 associated with HS and lower-energy diets (LS), respectively, similarly regulate pathways tied to volatile compound generation through ruminal bacteria. However, Pathway 4, which is unrelated to ruminal microbes, significantly, shapes lipid metabolism within the LL muscle, impacting LL intramuscular lipids, alcohols, and aldehydes (Zhang, Yuan, et al., 2022). In contrast, for Boer goats slaughtered at a slaughter weight below 50 kg with an equal amount of energy intake, the type of energy feed was not observed to exert a significant impact on IMF deposition and flavor of goat meat (Brand et al., 2018). This phenomenon can be attributed to the fact that goats primarily accumulate fat in the abdominal region and exhibit lower lipid deposition in the muscle (Tsitsos et al., 2022). Therefore, the influence of HS in sheep flavor profiles may be species-specific, involving complex metabolic processes governing biosynthesis of flavor compounds that require further elucidation.

3.1.2. Fermentation silage

Based on the silage categories outlined in Table 1, a recent study on the feeding of Tan sheep with three different silages showed that the use of alfalfa silage substantially reduced the hexanal content of sheep meat (concentrate control: 165.51 μg/kg, alfalfa silage diet: 8.91 μg/kg), whereas the content of 3-hydroxydodecanoic acid was elevated when mulberry leaf silage was used (Wang, Han, et al., 2022; Wang, Li, et al., 2022; Wang, Luo, & Wang, 2022; Wang, Zhao, et al., 2022). Excessive hexanal at low thresholds can produce an unpleasant odor; therefore, the reduced hexanal content resulting from the addition of alfalfa silage could improve sheep meat flavor.

3.1.3. Plant by-products

In ruminants, plant-based feeds, primarily consisting of crop residues, husks, plant cake meal, and forestry by-products, can be classified into distinct categories, such as by-product feeds, cereal feeds, and legume feeds based on their specific processing methods. Among these categories, plant by-product feeds are notable for their abundance in phytochemicals, while silage stands out for its enhanced palatability among ruminants.

As listed in Table 1, a comprehensive study on the addition of plant-derived feeds to sheep diets showed their capacity to influence FAs and volatile compounds associated with the flavor of sheep and goat meat, but do not produce negative odor in sheep meat, making them an ideal alternative feed. The utilization of rosemary residue (RR) as a grain substitute in the diet of Barbarine male sheep led to an elevation in the PUFA content in sheep meat, notably, increased levels of C18:2, C18:3, C20:4, C20:5, and C22:5 (Smeti et al., 2021). Among these, C18:2 and C18:3 were identified as the primary contributors to the development of the flavor of sheep meat. The addition of 200 g/kg of whole pomegranate by-product (WPB) to the diet of Comisana sheep to replace part of the corn diet resulted in higher concentrations of total PUFAs, vaccenic acid (C18:1 *t*11), rumenic acid (C18:2 *c*9) and volatile compounds (e.g., aldehydes, alcohols, ketones, and hydrocarbons) in the WPB-treated meat. Although the volatile compounds of meat in these two groups varied considerably in *E*-nose, the differences in sensory attributes between these two types of sheep meat could not be accurately determined because the sensory assessments performed by untrained panelists did not distinguish between differences in flavor attributes (Natalello et al., 2023). This indicated that by-products can increase the category and content of volatile compounds, but not necessarily the flavor of sheep and goat meat as assessed by sensory evaluation, which also correlates with whether or not the sensory evaluation team is trained. Similarly, herbaceous plants (*Juniperus* spp.) were utilized to replace cottonseed meal for feeding Rambouillet sheep, leading to the presence of seven specific volatiles in the resulting meat, namely, 1-pentanol, heptenal, pentanal, 1-(1H-pyrrol-2-yl)-ethanone, 2-heptanone, 6,7-dodecanedione, and butyric acid. Notably, these volatiles did not impart undesirable odors, which were unaffected by final FA composition and overall sensory profile (Kerth et al., 2018). Hence, utilization of alternative feeds does not negatively affect the flavor of sheep meat.

3.2. Feed additives

Feed additives can be classified into various categories, including

Table 1
Effects of different feeds on fatty acids and flavor in sheep and goat meat.

Type	Species/Muscle type	Experimental design	Fatty acid and flavor	References
Energy feed	Black Tibetan sheep/ *Longissimus lumborum* (LL) muscle	Twenty-seven 120-day-old rams were randomly assigned to three experimental groups of 9 replicates with high energy level (11.08 MJ/kg), medium energy level (10.12 MJ/kg), and low energy level (9.20 MJ/kg) for 120 days.	• High energy group contained valeric, isovaleric, butyric, propionic, acetic acids, which were dominated by alcohols. • Medium energy group was dominated by aldehydes. • Low energy group was dominated by ketones.	(Zhang, Han, Hou, Raza, Gui, et al., 2022)
	Boer goat/ *Longissimus lumborum* (LL) muscle	Twenty-four 18-week-old goat kids were allocated to three experimental groups of 8 replicates each with a low energy (9.7 MJ ME/kg feed), medium energy (10.2 MJ ME/kg feed) and high energy (10.6 MJ ME/kg feed) diet for 20 weeks.	• Meat from three energy groups exhibited beefy, oily and sweet associated aromas, whilst hints (low scores) of livery and metallic odors. • No aroma difference was observed among energy groups.	(Brand et al., 2018)
Fermentation silage	Hu sheep/ *Longissimus thoracis* (LT) muscle	Ninety-six 3-month-old lambs were randomly assigned to four groups, with 6 replicates in each group and 4 lambs in each replicate. Replacement by 0, 20, 40 and 60 % of maize silage with mulberry silage for 60 days.	• Feed replacement by 40 % had the highest monounsaturated fatty acid (MUFA) (C16:1) values and the lowest PUFA values, making it the optimal choice.	(Wang, Han, et al., 2022; Wang, Li, et al., 2022; Wang, Luo, & Wang, 2022; Wang, Zhao, et al., 2022)
	Tan sheep/ *Longissimus lumborum* (LL) muscle	Twenty-four 75 (±3)-day-old lambs were randomly assigned to four groups with 6 replicates each and each group was fed concentrate-based diet, corn silage-based diet, alfalfa silage-based diet and mulberry leaf silage-based diet for 80 days.	• Compared to control, corn silage group had increased levels of 14-octadecenal and dodecane, and decreased levels of 2′-hexyl-1,1′-bicyclopropane-2-octanoic acid methyl ester. • Compared to the control, the alfalfa silage had decreased concentrations of hexanal.	(Wang, Han, et al., 2022; Wang, Li, et al., 2022; Wang, Luo, & Wang, 2022; Wang, Zhao, et al., 2022)
Plant by-product	Comisana sheep/ *Longissimus thoracis et lumborum* (LTL) muscle	Seventeen 60-day-old male lambs were randomly divided into four groups, eight in the control group and nine in the treatment group, with the control feeding diet containing 20 % of whole pomegranate by-product for 36 days.	• The concentrations of total PUFA, vaccenic and rumenic acid were higher in WPB meat. • Most volatile compounds (i.e., aldehydes, alcohols, ketones, and hydrocarbons) were more concentrated in WPB meat than in the control group.	(Natalello et al., 2023)
	Barbarine sheep/ *Longissimus thoracis et lumborum* (LTL) muscle	Twenty-seven culled ewes were randomly divided into three groups of 9 replicates each. The Control group received 750 g of concentrate and 500 g of hay. The Myrt-H group received 750 g of concentrate and 500 g of M-Hay as a whole substitute to hay. Myrt-C group received 500 g of oat-hay, 350 g of concentrate, and 400 g of M-Conc in partial substitution to concentrate for 90 days.	• Long-chain PUFAs such as C20:3 and C20:4, vaccenic acid, and desirable fatty acids were higher in the Myrt-H group. • Substitution of conventional feedstuff with a dose of 87 % MR in diet could be an alternative to improve fatty acids composition.	(Tibaoui et al., 2020)
	Barbarine sheep/ *Longissimus thoracis et lumborum* (LTL) muscle	Twenty-four 3-month-old male lambs were randomly divided into three groups with 8 replicates each. Commercial concentrate (control group), rosemary residues (RR) plus 600 g faba bean (RRF group) and RR plus soybean meal (RRS group) for 65 days.	• The inclusion of RR in the concentrate increased the content of C18:2, C18:3, C20:4, C20:5, and C22:5.	(Smeti et al., 2021)
	Rambouillet sheep/ *Longissimus thoracis* (LT) muscle	Forty-eight 4-month-old lambs were randomly divided into six groups of 8 replicates each and fed six different roughages: either cottonseed hulls (CSH) or a ground woody product consisting of *J. pinchotii* (redberry juniper [RED]), *J. ashei* (blueberry juniper [BLUE]), *Juniperus monosperma* (one-seeded juniper [ONE]), *Juniperus virginiana* (eastern red cedar [ERC]), or *Prosopis glandulosa* (honey mesquite [MESQ]) for 57 days.	• Seven volatile aroma compounds were affected by dietary roughage source, including 1-pentanol, heptenal, pentanal, 1-(1H-pyrol-2yl)-ethanone, 2-heptanone, 6,7-dodecanedione, and butanoic acid. • Addition of four juniper or mesquite species can replace the control without adversely impacting fatty acid or sensory characteristics.	(Kerth et al., 2018)
	Arabian fattening sheep/ *Longissimus thoracis* (LT) muscle	Twenty-four 4-month-old male lambs were randomly divided into four groups with 6 replicates each and fed four different diets Standard concentrate diet, 7 % Roasted Canola Seed diet (RCS), 36 % Sugar Beet Pulp diet (SBP), SBP plus RCS diet (SBP + RCS) for 85 days.	• Replacement of barley with SBP increased content of IMF in sheep, without impacting sensory properties. • RCS supplementation of 7 % increased the content of C18:0, C18:1, C18:3, eicosapentaenoic acid, and docosahexaenoic acid, which could improve flavor of sheep meat.	(Asadollahi et al., 2017)
	Santa Inês sheep/ *Longissimus lumborum* (LL) muscle	Forty 120-day-old male lambs were randomly divided into five groups of 8 replicates each, and Tifton 85 hay was replaced with dehydrated ground guava agro-industrial waste (GAW) at 0 %, 7.5 %, 15 %, 22.5 %, and 30 % of dietary DM for 48 days.	• GAW increased 30 % GAW and IMF content by 0.56 %. • GAW did not affect sheep meat flavor.	(Nobre et al., 2020)

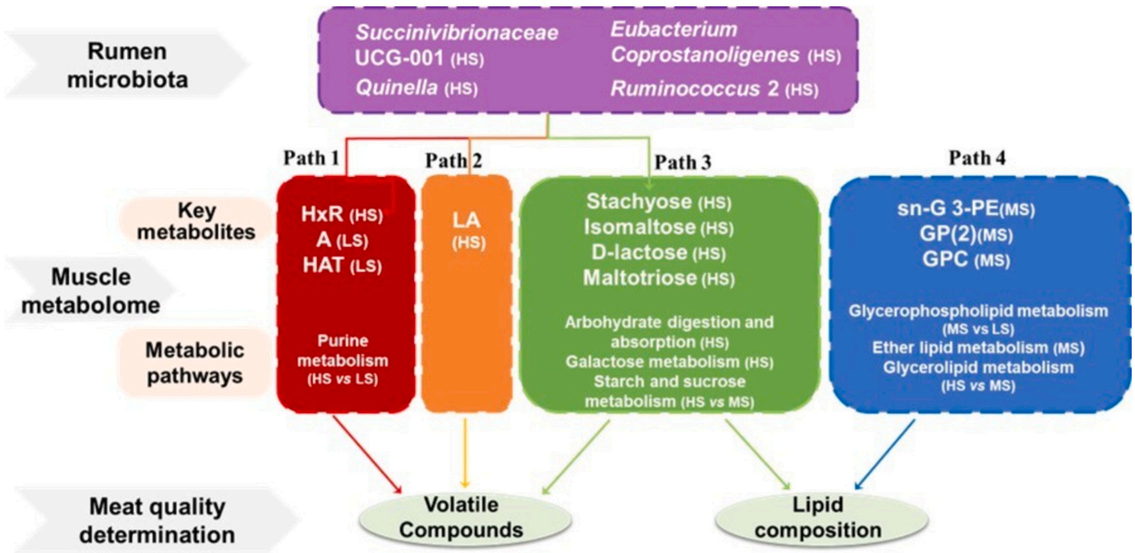

Fig. 2. The hypothesized pathways and potential mechanisms related to the changes of rumen microbiota, muscle metabolome and meat quality. Note: Red, yellow and green colors represent high expression in high-energy diet (HS) and blue color represents low expression in medium-energy diet (MS). Path 1 (red), Path 2 (yellow), Path 3 (green), Path 4 (blue). HS: high energy diet; MS: medium energy diet; LS: low energy diet. A: adenine; HAT: hypoxanthine; HxR: inosine; PE: phosphoethanolamine; GP (2): glycerophosphate (2); GPC: glycerophosphocholine; LA: linoleic acid; G: glycerol (within 24 h after slaughter).

natural plant extracts, fermented plant additives, lipid supplements, and microbial feed additives. Plant-based feed additives are most prevalent and are mainly used to improve the flavor of sheep and goat meat via the rumen microbiota. Moreover, some other feed additives modify the flavor of meat by affecting FAs associated with the characteristic flavor of sheep and goat meat.

3.2.1. *Natural plant extracts*

When utilized as feed additives, natural plant extracts exhibit no adverse effects on the flavor of sheep and goat meat (Tian et al., 2021). Moreover, they enhance meat aroma by diminishing unpleasant odors and introducing volatile flavor compounds, thereby enhancing the overall flavor profile. As listed in Table 2, the improved flavor of sheep meat by using plant extracts as feed additives was achieved by affecting flavor-related FAs and volatile compounds. Tian et al. (2021) reported that anthocyanin-rich PCP was introduced into the diets of Qianbei goats at two different additive rates, namely 0.5 g/d and 1 g/d, reduced total hydrocarbons, aromatic hydrocarbons, esters, and heterocyclic compounds, while increasing the diversity of flavor compounds and the total alcohol content of *Longissimus thoracis et lumborum* (LTL) muscle. This resulted in an increase in botanical, herbal, oleaginous, and fruity flavors in comparison to the control group. Natural plant extracts, especially *Allium mongolicum* Regel (AMR) extract, are rich in flavonoids, which can change the FA composition of sheep meat and further improve flavor. The addition of AMR extract to the diets of Small-tailed Han sheep led to a linear decrease in C18:0 and SFA in LT muscle, a decline in MOA concentration, and a linear increase in eicosapentaenoic acid and monounsaturated fatty acid (MUFA) (Liu et al., 2019). The rational use of plant residues as feed additives can enhance meat flavor while improving economic efficiency (Wang et al., 2023). Addition of 10 % Jasmine flower residue to Nubian goat diets increased the beneficial n-3 PUFA (C18:3 and C20:5) content in meat, and increased acetaldehyde and hexanal appropriately to enhance the fruity flavor in meat (Wang et al., 2023). Hence, plant extracts can enhance the flavor profile of sheep meat and mitigate unpleasant odors.

3.2.2. *Lipid supplements*

The addition of lipids to diet can enhance feed energy efficiency, facilitating the direct utilization of long-chain FAs in the lipid metabolism pathway. Moreover, it can inhibit the biohydrogenation of unsaturated fatty acid (UFA) by ruminants during digestion, thereby elevating polyunsaturated lipid levels and enhancing the flavor of sheep and goat meat. The inclusion of 0.1 % macadamia oil in the diets of Santa Inês × Dorper male sheep can increase the levels of IMF and C18:3 in the LL muscle (Dias Junior Paulo Cesar et al., 2022). When crossbred (Santa Ines × Dorper) sheep were fed with diets containing different levels of Buriti oil (BOIL) – 0, 12, 24, 36, and 48 g/kg dry matter (DM), a linear reduction in the concentration of 16:0 and C9–18:1 and an increase in the levels of C18:0 and C20:3 was observed in the goat meat as BOIL intake increased. Notably, addition of BOIL at 24, 36 and 48 g/kg DM in the sheep diet could improve "goaty" flavor and aroma intensity of meat based on sensory analysis, while also slightly altering the FA levels in the meat (Diogenes et al., 2022). Therefore, lipid supplements mainly alter the FAs of sheep meat and increase volatile compounds, and reduce unpleasant odors in sheep meat.

3.2.3. *Microbial feed additives*

Microbial feed additives can modify the composition of volatile compounds in sheep meat. Liu, Hou, et al., 2022; Liu, Hui, et al., 2022; Liu, Li, et al., 2022 reported that utilization of dietary probiotic supplementation in sheep resulted in the decreased content of aldehydes, nonanal, and decanal in LT muscle, and an increase in the concentration of 1-pentanol, 1-hexanol, and 2,3-octanediones in LT muscle. These alterations contributed to a change in the flavor profile of sheep meat, with a decrease in aldehydes and an increase in alcohols being particularly favorable to meat flavor. Similarly, probiotics supplementation (1 g/d of *Clostridium butyricum*) in goats revealed an increased level of 18:3n-3, 20:5n-3 and PUFA and a decrease in 16:0 content in meat (Zhang et al., 2024). It is worth noting that further research is required to fully comprehend how dietary probiotic supplementation impacts gut microbiota and subsequently influences changes in FAs and volatile compounds.

3.3. *Feed management*

The variations in feeding systems can lead to diverse outcomes in terms of FAs and volatile compounds. This depends partly on the type of pasture and partly on the duration of grazing and the amount of exercise. The diversity of plant species distribution in grazing pastures affects the proportion of unsaturated fatty acids in sheep meat, which has the

Table 2
Effects of different feed additives on fatty acids and flavor in sheep and goat meat.

Type	Feed additives	Species/Muscle type	Experimental design	Fatty acids and flavor	References
Natural plant extracts	• 3 % *Perilla frutescens* seeds	Tan sheep/ *Longissimus lumborum* (LL) muscle	Forty-five 6-month-old male lambs were randomly divided into five groups of 15 animals each with three blocks (pens) of 5 lambs each with a 48-day feeding cycle.	• Increased levels of acetaldehyde and 1,2,4-trimethylbenzene gave fruity odor and violet aromas.	(Yu et al., 2024)
	• 4 % mimosa (*A. mearnsii*; condensed tannins; MI) • 4 % chestnut (*C. sativa*; hydrolysable ellagitannis; CH) • 4 % tara (C. spinose; hydrolysable gallotannins; TA)	Sarda × Comisana sheep/ *Longissimus thoracis et lumborum* (LTL) muscle	Thirty-six 2-month-old male lambs were randomly divided into four groups of 9 replicates each and fed in a single pen with a 75-day feeding cycle.	• An inclusion rate of 4 % tannin extracts did not affect the sensory properties of the meat.	(Del Bianco et al., 2021)
	11 mg/kg, 22 mg/kg, or 33 mg/ kg *Allium mongolicum* Regel extract	Small-tailed Han sheep/ *Longissimus thoracis* (LT) muscle	Sixty 6-month-old sheep were randomly divided into four groups of 15 replicates each with a 60-day feeding cycle.	• A linear decrease in C18:0 and SFA, a decrease in MOA concentration was observed. • A linear increase in eicosapentaenoic acid and MUFA was observed.	(Liu et al., 2019)
	10 % Jasmine flower residue (JFR)	Nubian goat/ *Longissimus thoracis* (LT) muscle	Twenty-four 4-month-old male goats were randomly divided into 2 groups of 12 replicates each with a 45-day feeding cycle.	• The addition of JFR increased the content of n-3 PUFA (C18:3 and C20:5) and reduced the content of C24:1 and SFA (C20:0 and C22:0). • The addition of JFR increased the content of acetaldehyde and hexanal in the meat and improved the umami, saltiness, and richness of the meat.	(Wang et al., 2023)
	• 0.5 g/d anthocyanin-rich purple corn pigment (PCP) • 1 g/d PCP	Qianbei Ma goat/ *Longissimus thoracis et lumborum* (LTL) muscle	Eighteen 4-month-old goat kids were randomly divided into three groups of 6 replicates each and fed in a single pen for 60 days.	• The addition of PCP increased flavor compound types and total alcohol level (12.15 %), whereas it decreased total hydrocarbons (1.99 %), aromatics (1.085 %), esters (4.27 %), and miscellaneous compounds (4.91 %). • The addition of PCP to the diet enriched vegetal, herbaceous, greasy, and fruity flavors.	(Tian et al., 2021)
Lipids supplements	• 0, 12, 24, 36 and 48 g/kg dry matter (DM) Buriti oil (BOIL)	Santa Inês × Dorper sheep/ *Longissimus lumborum* (LL) muscle	Forty 120-day-old lambs were randomly divided into five groups of 8 replicates each and fed in a single pen for 56 days.	• The addition of BOIL increased the content of C18:0 and decreased the content of C16:0 in meat. • Feeding more than 24 g/kg DM of Buriti oil alleviated unpleasant odor.	(Diogenes et al., 2022)
	• 0.1 % Live weight macadamia oil (MO) • 0.1 % Live weight MO + vitamin E (500 mg/kg DM) (MOVE)	Santa Inês × Dorper sheep/ *Longissimus lumborum* (LL) muscle	Thirty 70 ± 10-day-old lambs were randomly divided into 3 groups of 10 replicates each and fed in a single pen for 60 days.	• The addition of MO increased IMF by 0.84 %. • The addition of MO increased C18:3 in meat by 0.08 % and improved meat flavor.	(Dias Junior Paulo Cesar et al., 2022)
	• 4 % Babassu oil (BAO) • 4 % Buriti oil (BUO)	Dorper × Santa Inês sheep/ *Longissimus lumborum* (LL) muscle	Twenty-one 123 ± 12 day old lambs were randomly divided into three groups of 7 replicates each and fed for 60 days.	• The addition of BUO increased IMF content by 1.5 %. • The addition of BAO increased medium chain fatty acids in sheep meat. • Meat sensory characteristics were not affected by babassu oil or buriti oil.	(Parente et al., 2020)
	• 30 g/d Rumen protected fat (RPF)	Saanen goat/ *Longissimus thoracis* (LT) muscle	Thirty-two 3-month-old lambs were randomly divided into four groups of 8 replicates each and fed for 60 days.	• The addition of RPF increased IMF content. • The addition of RPF supplementation increased the content of total FA, 16:0, 18:1 *c*9, 20:2n-6, SFA and MUFA.	(Zhang et al., 2024)
Microbial feed additives	• 10 g Probiotic/d (PRO)	Sunit sheep/ *Longissimus thoracis* (LT) muscle	Twenty-four 90-month-old lambs (12 rams and 12 ewes) were randomly divided into three groups of 4 replicates each and fed for 60 days.	• The addition of PRO altered the composition of volatile flavor compounds, such as nonanal, undecanal, 1-pentanol, 1-hexanol, and 2,3-octanedione.	(Liu, Hou, et al., 2022; Liu, Hui, et al., 2022; Liu, Li, et al., 2022)
	• 1 g/d *Clostridium butyricum* (CB)	Saanen goat/ *Longissimus thoracis* (LT) muscle	Thirty-two 3-month-old lambs were randomly divided into four groups of 8 replicates each and fed for 60 days.	• CB supplementation increased the content of 18:3n-3, 20:5n-3 and PUFA, but it decreased the content of 16:0 without altering the profiles of other FA.	(Zhang et al., 2024)

potential to influence the content of volatile flavor compounds (Kearns et al., 2023). Grasses that are dominant in grazed grasslands, such as *Achnatherum splendens*, *Lolium perenne*, all of which reduce the n-6:n-3 ratio in grazing sheep and improve the flavor of sheep meat (Echegaray, Dominguez, Bodas, et al., 2021; Echegaray, Dominguez, Cadavez, et al., 2021; Luo et al., 2019). Table 3 summarizes the variations in FAs and volatile compounds observed in sheep or goat meat when comparing grazing and housed feeding systems. Grazing-based feeding systems have consistently provided superior flavor profiles in most studies. Luo et al. (2019) reported a decline in intramuscular fat (IMF) content from 4.996 % to 3.390 %, accompanied by decreases in aldehydes and ketones (specifically hexanal, nonanal, and 2,3-octanedione) and increases in C18:3, eicosadienoic acid, and alcohols (1-pentanol and 1-hexanol) in grazing sheep, as compared to Mongolian sheep fed a basal diet. Meat from pastured sheep tended to exhibit a better flavor. The reduction in IMF was attributed to the fact that grazing enhanced physical activity in sheep and goat, resulting in higher fat utilization and lower IMF levels. A reduction in IMF also leads to a reduction in volatile flavor compounds, but an increase in the number of volatile flavor compounds (Luo et al., 2019). The rise in flavor-related FAs attributed to grazing is intricately linked with rumen microorganisms. The levels of ALA and conjugated LA were positively correlated with the abundance of *Butyrivibrio_2*, while the relative abundance of *Butyrivibririo_2* was increased in the rumen of Sunit sheep with pasture feeding (Wang, Gao, Wang, et al., 2021; Wang, Luo, Wang, et al., 2021; Wang, Wang, Chen, et al., 2021; Wang, Wang, Zuo, et al., 2021). Grazing also results in a reduction in the relative abundance of the genus *RC9_gut_group*, a biomarker of lipid deposition, so it can be inferred that grazing leads to a reduction in lipid deposition, which in turn affects the content of volatile flavor compounds (Cheng et al., 2022; Wang, Gao, Wang, et al., 2021; Wang, Luo, Wang, et al., 2021; Wang, Wang, Chen, et al., 2021; Wang, Wang, Zuo, et al., 2021). Thus, grazing can increase the diversity of rumen bacteria and feeding pasture may improve meat flavor.

The natural pasture inhibited rumen biohydrogenation and contained higher levels of flavor-imparting PUFA, especially n-3 PUFA, which can improve the flavor of sheep meat. Although the flavor of grazing has been found to be superior to that of indoor feeding, grazing can cause nutritional imbalances, indoor feeding is characterized by complete nutrition. Indoor feeding is characterized by a full range of nutrients, resulting in improved flavor (Wang, Gao, Wang, et al., 2021). Therefore, strategically combining grazing and indoor feeding, along with appropriate pasture and concentrate management, can optimize the flavor of sheep meat. Wang, Gao, Wang, et al. (2021) divided Tan sheep into five groups based on grazing time, including 12 h/d, 8 h/d, 4 h/d, 2 h/d, and 0 h/d. It was observed that grazing sheep effectively reduced the level of aldehydes, which can contribute to unpleasant odors.

Grazing for 2 h/d not only increased the variety of volatile flavor compounds but also resulted in higher levels of IMF in the LT muscle of the sheep. This grazing duration can be adjusted based on consumer preferences. Therefore, a combination of optimal grazing time and appropriate concentrate supplementation represents a more effective strategy for managing the quality of sheep and goat meat.

Table 3
Effects of forage and pasture types under different feeding management on fatty acid composition and flavor of sheep and goat meat.

Species/ Muscle	Experimental design	Fatty acids and flavor	References
Mongolian sheep/ *Longissimus thoracis* (LT) muscle	Twenty-four 3-month-old lambs were randomly divided into 2 groups of 12 replicates each. Pasture grass (PG group) was fed in an enclosure and mixed diet group (M group) was free-ranging in a semi-arid desert savannah, and both groups were fed for 6 months.	• PG group contained higher C18:3 and C22:3 than the mixed diet. • The levels of hexanal, nonanal, and 2,3-octanedione were significantly lower in meat of PG group. • The levels of 1-pentanol and 1-hexanol were higher in meat of M group.	(Luo et al., 2019)
Tan sheep/ *Longissimus lumborum* (LL) muscle	Twenty-four lambs, 120 days old, were randomly divided into three groups of eight replicates each. They were divided into indoor feeding group twice; 4 h artificial pasture grazing with once a day indoor feeding group; and full-time artificial pasture grazing group. A total of 90 days were fed.	• Pure artificial pasture grazing and artificial pasture grazing with indoor feeding increased the level of PUFA, especially the concentration of n-3 PUFA.	(Wang, Gao, Wang, et al., 2021)
Sunit sheep/ *Longissimus thoracis* (LT) muscle	Twenty-four 9-month-old sheep were randomly divided into 2 groups of 12 replicates each. Sheep in the Pasture feeding group (6 rams and 6 ewes) were left to graze freely for 3 months, and sheep in the barn feeding group (5 rams and 7 ewes) were housed for 3 months.	• Pasture feeding group sheep meat contained higher content of n-3 PUFA than meat of barn feeding group sheep.	(Wang, Gao, Wang, et al., 2021; Wang, Luo, Wang, et al., 2021; Wang, Wang, Chen, et al., 2021; Wang, Wang, Zuo, et al., 2021)
Tan sheep/ *Longissimus thoracis* (LT) muscle	Fifty 3-month-old lambs were randomly divided into 5 groups with 10 replicates each. The 52 ha of grassland was fenced into four equal areas and grazing time 12 h/d, 8 h/d, 4 h/d, 2 h/d were grazed on 13 ha of natural grassland, and the rest of the time and the no-grazing group were fed individually. A total of 120 days were fed.	• Sheep grazing for 2 h/d with supplement and indoor supplementary feeding sheep meat had a higher level of intramuscular fat (IMF). • Grazing sheep meat had a wider range of volatile compounds, compared to indoor supplementary feeding sheep, but lower levels of aldehydes and total volatile compounds.	(Wang, Z. Z. Wang, et al., 2021a)
Erlangshan white velvet goat/ *Longissimus thoracis* (LT) muscle	Eighteen 5-year-old male goats were divided into two groups (grazing on flatland and mountain range) with 9 replicates per group from two areas with about 0 % and 40 % inclination and fed on natural pasture.	• Grazing on flatland group increased the contents of monounsaturated fatty acids (MUFA), PUFA and volatile compounds, but decreased the content of saturated fatty acid (SFA). • The key flavor compounds in both groups included hexanal, heptanal, (E)-2-octenal, octanal, nonanal, decanal, (E)-2-nonenal, and 1-octen-3-ol. • 1-Octen-3-ol and (E)-2-nonenal were the most contributing flavor compounds in the grazed on flatland and mountain range groups.	(Dou et al., 2023)

3.4. Sex and age

Both age at slaughter and sex can affect the proportion of IMF, lipids, FAs, and volatile compounds, which can exert an impact on the flavor of sheep and goat meat. Sex can indeed affect the FA composition and flavor intensity associated with the flavor of sheep and goat meat. It has been shown that female sheep tend to have higher IMF content and FAs associated with the flavor of sheep meat, compared to male sheep (Yousefi et al., 2019). Compared to *Gluteus medius* muscle of male Romanov sheep meat, the contents of 10-heptadecenoic acid (C17:1), C18:2 and total PUFA in female sheep meat were 72.5 %, 16.0 % and 10.7 % higher, respectively, which are conducive to the overall flavor of sheep meat (Klupsaite et al., 2022). However, male sheep exhibit a higher flavor intensity, characterized by unpleasant odors, primarily due to hormonal secretions. In the case of Rubia de El Molar Autochthonous sheep, male sheep meat had a higher flavor intensity score of 5.52, compared to female sheep meat of 5.06 (total 10.00) (Miguel et al., 2021b). It can be proposed that this intensity of flavor is mainly related to the "gamy" flavor, so it is possible to improve the unpleasant odor of male sheep and goat by modifying the IMF content and fatty acid categories in the meat of sheep and goat through castration, thus affecting the volatile compounds in the sheep and goat meat (Miguel et al., 2021b). In Hu sheep, IMF increased in castrated sheep and a similar trend was observed in IMF of castrated Angora goat (Erol & Unal, 2022; Li et al., 2020). The levels of 1-octen-3-ol and hexanol, volatiles associated with the flavor of sheep, exhibited a significant increase in the meat of castrated Hu sheep, with 1-octen-3-ol content being 1.57 times higher than that observed in uncastrated Hu sheep (Li et al., 2020). In addition, the variation in FAs due to sex differences was also reflected across different muscle parts. For example, in Rubia de El Molar sheep, there was a significant difference between males and females in the quadriceps femoris muscle and biceps femoris muscle, with FA contents of 2.4 % and 2.9 %, respectively. In contrast, in the biceps femoris muscle and supraspinatus muscle, these differences were only associated with weight gain (Miguel et al., 2021a). And all of these changes have the potential to ultimately affect the flavor profile of sheep and goat meat.

Age exerts a significant impact on both FA composition and aroma profile of sheep and goat meat. Distinctive age-related differences are distinguished in the FA composition, particularly in the leg muscle (*M. biceps femoris*), in male Polish Carpathian native goats aged 9 and 12 months. Specifically, meat from 9-month-old goats exhibited higher levels of palmitic acid and C22:1, whereas meat from 12-month-old goats contained elevated quantities of PUFA, including C18:2, ARA, and docosanoic acid (Kawecka & Pasternak, 2022). These variations in fatty acid composition influence the categories of volatile flavor compounds. Flavor compounds can serve as distinguishing factors among sheep of the same breed but differing in age. Specifically, five volatile compounds pentanal, 3-ethyl-2-methyl-1,3-hexadiene, 2-octenal, hexanal, and hexadecanal have demonstrated the ability to distinguish between 7-month-old and 9-month-old native Polish sheep of the Wrzosówka breed (Gasior et al., 2021). The presence of different volatile compounds at 2, 6, and 12 months of age can be used as markers to differentiate Jingyuan sheep at different ages (Wang, Han, et al., 2022; Wang, Li, et al., 2022; Wang, Luo, & Wang, 2022; Wang, Zhao, et al., 2022). Their significant volatile compounds were mainly 2-amyl furan, 1-octen-3-ol, 1-hexanol, and heptanol at the age of 2 months, cis-3-hexenol, 2-methyl-1-propanol, (E)-2-hexen-1-ol, and (E)-2-pentenal at 6 months of age and 2-pentanone, valeraldehyde, and heptanal at 12 months of age (Wang, Gao, Wang, et al., 2021; Wang, Luo, Wang, et al., 2021; Wang, Wang, Chen, et al., 2021; Wang, Wang, Zuo, et al., 2021). These markers allow a clearer distinction between sheep and goats of different ages and an understanding of the effect of changes in volatile flavor compounds on flavor of sheep and goat meat in that age group.

Age plays a significant role in the presence of unpleasant odor in sheep and goat meat. Specifically, flavors characterized as "goaty" and "gamy" flavor have been linked to the elevated levels of BCFA in sheep and goat meat, with these flavors becoming more pronounced as the animals age. In Dorset × Hampshire breed ewes fed the same diet, mature sheep had a greater intensity of "goaty" flavor than lamb and yearling sheep (Jaborek et al., 2020). Similarly, the castrated "Mestiço" male goats slaughtered at 175, 210, 265 and 310 days were found to have the highest flavor scores but the lowest number of volatile compounds based on sensory evaluation. The intensity of the "goaty" flavor increases with the age at slaughter (Madruga et al., 2000). BCFAs have been found to have little or no effect on the odor of sheep meat until sheep are older than one year, but it has a greater effect on odor of sheep and goat meat after 2 years (Young et al., 2003). BCFAs associated with unpleasant odors were not detected in 4-month-old Mongolian sheep (Luo et al., 2019). However, MOA was identified in the LT muscle of 6-month-old Small-Tailed Han sheep, which may be breed-related (Liu et al., 2019). Thus, BCFAs associated with undesirable odors can increase with age, leading to a more pronounced "goaty" and "gamy" flavor in sheep and goat meat after one year. However, some breeds may manifest these flavors before one year, indicating a breed-dependent variation. Thus, BCFA associated with undesirable odors can increase with age, with most sheep and goat meat with more pronounced "goaty" and "gamy" flavor in sheep and goat meat after one year, but some breeds may exhibit these characteristics before reaching one year of age.

3.5. Species and breeds

Substantial variations can be observed in the IMF content, FA composition and flavor compounds among different species or breeds of sheep and goats. Compared to goat meat, sheep meat is more intense in aroma and has a higher IMF content (Babiker et al., 1990). As a result, it is abundant in FAs and has a greater variety of volatile flavor compounds. Madruga et al. (2013) reported that flavor differences between Saanen goats and cross Suffolk lambs, indicating that lambs exhibited a more intense flavor than goat meat due to a higher content of lipid-derived volatile compounds. Volatile compounds resulting from the oxidation of LA were found at elevated levels in lamb meat, due to its higher concentration of LA, whereas compounds formed from ALA were more abundant in goat meat. This fact suggested that sheep meat may contain a higher concentration of volatile flavor compounds compared to goat meat, resulting in a potentially more complex flavor profile. However, the majority of volatile compounds in both sheep and goat meat belong to the categories of aldehydes, alcohols, and ketones, with aldehydes being particularly influential. Notably, the key volatile compounds in Inner Mongolian goat meat encompass hexanal, heptanal, octanal, nonanal, decanal, (E)-2-octenal, (E)-2-nonenal, and 1-octen-3-ol (Dou et al., 2023). Similarly, the meat of Inner Mongolian sheep primarily contains hexanal, heptanal, octanal, nonanal, decanal, and (E)-2-decenal as the characteristic volatile compounds (Liu, Hou, et al., 2022; Liu, Hui, et al., 2022; Liu, Li, et al., 2022). Hexanal, heptanal, octanal, nonanal and decanal are common volatile compounds in Inner Mongolian sheep and Inner Mongolian goat meat. However, 1-octen-3-ol, (E)-2-nonenal, and (E)-2-octenal in Inner Mongolian goat meat can impart additional mushroom, smoky, and fatty flavors to the meat (Dou et al., 2023). Due to the higher fat content in sheep, which leads to a higher content of volatile flavor compounds, the flavor of sheep meat is more intense at equal thresholds (Schonfeldt et al., 1993). Consequently, variations in the concentration and types of volatile compounds serve as the fundamental cause for the flavor difference in sheep and goat meat.

There were some differences in FA and volatile compounds between different breeds of sheep or goats. By comparing the metabolism of Lubei white goats (LBB), Boer goats (BE) and Jining grey goats (JNQ), Wang et al. (2019) found that there were significant differences in FAs, aldehydes, ketones and lactones in the meat of these three goats (e.g. compared with BEs, JNQs contain significantly higher amyl salicylate and hexyl salicylic acid, both described as "floral"), which may underlie their flavor nuances. The variations in volatile compounds can serve as distinguishing factors for identifying sheep breeds. Zhang et al. (2020) reported that involving three different sheep breeds, Tan and Hu sheep had higher accumulations of IMF and SFA compared to Dorper sheep. However, Tan had a lower proportion of C18:2, ALA, and PUFA compared to Dorper sheep. Notably, (E)-2-hexenal was exclusively found in Tan sheep, while (E)-2-nonenal and (E,E)-2,4-nonenal were exclusively found in Dorper sheep, with Hu sheep containing the lowest amount of volatile compounds. In another study comparing Hu and Tan sheep, no significant difference was found in their IMF content. However, Tan sheep had lower levels of SFAs, (E)-2-nonenal, and no significant differences were observed in the 18 major flavor-active volatile compounds (Li, Tang, Yang, et al., 2023; Li, Zhao, Dai, et al., 2023; Li, Zhao, Jian, et al., 2023).

Further crossbreeding between different breeds has the potential to enhance sheep production and improve the flavor of sheep meat. Crossbreeding has an impact on the quality of sheep by influencing FA profiles and volatile compounds of meat. Lu et al. (2022) reported that compared to Hu × Hu (HH) sheep, Southdown × Hu (NH) and Suffolk × Hu (SH) crossbred sheep contained a higher content of SFA, C18:2, and C18:3, and lower content of MUFA. The distinctive FA profile enabled the differentiation of HH sheep from SH sheep by developing flavor fingerprints and employing principal component analysis models. These findings suggested that sheep and goats exhibit significantly higher levels of IMF, FA, and volatile compounds compared to different breeds of sheep and goats. Combination of superior traits can be used as an important factor to improve the flavor of sheep and goat meat through crossbreeding. Different volatile compounds can also be used as markers to differentiate between different sheep or goat breeds, and the effect of crossbreeding on meat quality is achieved through changing FA composition and volatile compounds.

3.6. Other factors

Different muscle types and cuts of sheep and goat also affect their FA composition and flavor. The PUFA content in LL muscle of fattened Polish Merino breed sheep was significantly lower than that of GM muscle. Different volatile compounds were observed in different muscle parts of sheep meat. By observing the characteristic volatile compounds in sheep brisket (SBT), sheep loin (SLN), sheep rib (SR) and sheep leg (SLG) in the Small-tailed Han Sheep × Mongolian Sheep crossbreed. Qi et al. (2023) found that hexanal was the highest in SBT, followed by nonanal, and the lowest was octanal; octanal was the highest in SLG, and the least was (E)-2-heptanal; however, dodecanal was only present in the SLG. Therefore, the variations in the aroma characteristics of different muscle parts of sheep meat are due to the variations in the amount and content of volatiles. Trained sensory panelists can distinguish between animals of varying body weights. Miguel et al. (2021b) reported that the flavor profiles of Rubia de El Molar sheep with different body weights (10, 15, 20, and 25 kg) by a panel of trained experts found that fattening lamb had higher sensory scores. This may be because heavy sheep contain more IMF and thus more volatiles and a richer flavor.

In grazing conditions, Tsigai and Suffolk crossbreed lamb exhibited variations in the proportions of specific FAs in their IMF when comparing weaned and unweaned lamb. Weaned lamb demonstrated higher proportions of C18:2, C20:4, C18:3, C20:5, C22:5, C22:6, and total PUFA in their IMF compared to unweaned lamb. Conversely, unweaned lamb displayed higher proportions of SFA and MUFA. These differences in FA composition suggested that weaned lamb may have a better flavor profile due to the presence of a greater number of FAs associated with flavor of sheep meat (Janíček et al., 2021). Therefore, in addition to significant nutritional factors, differences in various muscle parts, weaning status, and body size at similar age also influence the FAs associated with meat flavor.

4. Post-mortem factors affecting the flavor of sheep and goat meat

Post-mortem factors primarily include non-thermal processing activities, such as aging, freezing, dry curing, and packaging, as well as thermal processing methods. These post-mortem factors collectively exert a substantial influence on the overall flavor of sheep and goat meat (Tibaoui et al., 2020). Different factors such as temperature, light, and oxygen can speed up meat oxidation during storage, leading to the declined quality associated with rancidity and off-flavors, while a low degree of lipid oxidation and dry curing treatment can enhance the flavor of meat (Kanokruangrong et al., 2018). The generation of flavor in sheep and goat meat is predominantly related to thermal processing. This process entails the thermal degradation of UFA present in sheep and goat meat, leading to lipid oxidation and the release of various volatile compounds, such as aldehydes, ketones, alcohols, acids, and furans, which constitute a significant component of the flavor profile of sheep and goat meat (Bleicher et al., 2022; Fu et al., 2022).

4.1. Non-thermal processes

The flavor of goat and sheep meat can be influenced by various non-thermal processing methods, including aging, freezing, dry curing, fermentation, and packaging. These processes impact lipid oxidation, which in turn affects the flavor of sheep and goat meat. As lipid oxidation typically exerts an adverse impact on meat and meat products, in some cases, it contributes to desirable aromas (Guo et al., 2019; Xu et al., 2023). Lipid oxidation-derived compounds formed during aging or dry curing play a pivotal role in shaping the distinctive aromas of these types of meat products, a highly valued attribute among consumers (Dominguez et al., 2019).

4.1.1. Aging

Lipid oxidation, which involves the aging process of meat after slaughter, can significantly contribute to the flavor development of goat and sheep meat, but due to the difference in the intramuscular fat, the degree of lipid oxidation and the optimal aging time are different. The content of aldehydes (e.g. hexanal, heptanal, octanal, nonanal, and decanal) as well as alcohols (e.g. 1-octanol) in sheep muscle stored at 4 °C progressively increased with extended aging time, particularly from 0 to 4 days after slaughter, where aldehydes contributed to the development of green grass, nutty, and fatty flavor, while 1-octanol influenced the flavor during post-mortem aging, imparting fatty, waxy, oily, walnut-like, and burnt aroma to the flavor of meat (Dou et al., 2022). The extended aging time has a negative effect on sheep meat flavor. A recent study on 7-month-old Tan sheep meat stored at 4 °C has revealed two phases in aroma development. The short-term aging (0–3 days) was influenced by acyl carnitine and DGs, with key volatile compounds including heptanol, 1-octen-3-ol, 6-methyl-2-heptanone, 3-heptanone, 2-pentylfuran, and octanol. In the later stage of aging (3–7 days), the reduction of hexanal, glutaraldehyde, hexanol, octanol, 6-methyl-2-heptanone, heptanol, 1-octanol-3-ol, styrene, and benzaldehyde was the main reason for the altered flavor profile, and lipid metabolism regulated the volatile compounds to a lesser extent at this stage (Xu et al., 2023). The flavor of sheep meat can decrease in the later stage of aging (3–7 days). Therefore, a comprehensive analysis of the aging stages of sheep meat is optimal at 3–4 days.

Interestingly, compared with sheep meat, goat meat exhibited improved flavor during extended aging periods. In the meat of goat fed with red orange and lemon extract (RLE), the flavor quality exhibited a progressive improvement over extended periods of time (1, 3, and 7 days). Notably, the addition of RLE did not have a significant impact on the flavor of goat meat. Given the precise reasons remain uncertain, this improvement in flavor could be attributed to the antioxidant activity in the feed (Sgarro et al., 2022). However, it is worth noting that no antioxidant assays were conducted on goat meat in this study, so the antioxidant activity possessed by RLE may extend the aging time and thus enhance flavor in the later stages of aging, or it may be an inherent difference between the two species, with goats having lower levels of IMF and less lipid oxidation than sheep. These findings suggested that the optimal chilling time for sheep is 3–4 days at 4 °C, while for goats, the chilling time can be extended up to 7 days at 4 °C. Therefore, an appropriate aging time has a positive effect on the flavor of sheep and goat meat.

The variations in volatile compounds in sheep meat attributed to different feeding methods were no longer discernible after 24-h refrigeration. Both grazing and indoor housing led to elevated levels of alcohols, aldehydes, and ketones in Sunit sheep meat. However, the numbers of volatile compounds in grazed sheep consistently remained fewer than those found in indoor feeding sheep (Yang, Li, et al., 2022; Yang, Liu, et al., 2022). Notably, the distinctions in volatile compounds resulting from these two feeding methods disappeared after 24-h aging. Therefore, aging has effectively mitigated or even eliminated the differences in sheep flavor caused by different feeding methods and has accelerated the transition from traditional grazing to indoor feeding.

Various aging methods can exert distinct impacts on the volatile compounds and flavor of sheep meat. Sheep meat patties were aged for 19 days using both dry (Dry ager® cabinet, 80–85 % relative humidity, 0–2.5 °C) and wet (vacuum-packed in Cryovac ultra-high leak-proof bags, 0–2 °C) methods. Dry aging led to higher levels of most aldehydes, alcohols, and alkanes, while wet aging resulted in elevated concentrations of (E)-2-heptanal, 2-ethyl-1-hexanol, and 1-octen-3-one. Check-all-that-apply analysis revealed distinct flavor profiles, with dry-aged sheep meat patties conferring roasted, fried, and cooked meat flavor, while wet-aged sheep meat patties conferring "goaty", "fecal", "animal", and "barnyard" flavor (Hastie et al., 2022). The overall flavor of the wet-aged patties was more intense compared to that of the dry-aged patties, likely due to the greater impact of certain volatile compounds, such as 1-octen-3-one, which was three times more concentrated in the wet-aged patties and contributed to a more metallic taste. Although dry aging exposed the meat to air, resulting in increased lipid oxidation, this process may not have produced sufficient rancid flavors. Instead, it likely enhanced caramelized and roasted flavors through the formation of pyrazines resulting from protein browning. Additionally, preferences for the two aging methods varied among individuals.

4.1.2. Frozen storage

The duration and temperature of frozen storage can have a certain influence on the flavor of meat. A recent study comparing conventionally frozen (CF, −18 °C), low-temperature frozen (LF, −40 °C), and ultra-low-temperature frozen (ULF, −80 °C) over a period of 0–180 d revealed that a significantly decreased concentration of aldehydes, alcohols, ketones, acids, and olefins occurred with an extended storage time, although the levels of retained volatile compounds were higher in both LF and ULF method, compared to CF (He et al., 2022). This phenomenon was due to the faster freezing rate. Therefore, it is recommended to use LF or ULF storage methods to prolong the storage time while preserving the meat flavor.

The ideal period of frozen storage can be determined by monitoring alterations in flavor compounds. He et al. (2022) refrigerated sheep meat at −18 °C for varying durations, ranging from 3 to 90 days, and found that the highest concentration of volatile compounds was detected after 60 days of refrigeration, including (E)-2-octene, 3-cyclohexadiene, styrene, trans-2-hexenal, 2-octanone, 2,6-dimethylpyrazine, and 2-heptanone. Additionally, volatile compounds, such as 2,4-heptadienal, which imparts grassy, fatty, and spine-like flavors, and furanol, known for its sweet bread aroma, existed only in the samples stored for 60 days. Consequently, frozen storage for 60 days at −18 °C is optimal for achieving the ideal flavor in sheep meat.

4.1.3. Fermentation and dry curing

Microbial fermentation can remove unpleasant odor and improve the flavor of sheep and goat meat. The leg meat of 1.5-year-old sheep was sliced, inoculated with *Lactobacillus* and *Staphylococcus carnosus*, and fermented for 36 h. Subsequently, it was dried at 60 °C for 6 h and finally baked at 180 °C for 5 min to prepare dried sheep meat, thereby eliminating unpleasant odors, such as MOA, MNA, and EOA (Zhou et al., 2022). A mixture of *Pediococcus acidilactici* and *Rhizopus oryzae* strains was employed in the inoculated fermentation of dried sheep meat sausages, resulting in increased types of volatiles and higher total content of aldehydes and esters by the end of fermentation, thus achieving superior flavor compared to traditional methods (Jiang et al., 2023). Dry curing can be used to preserve and enhance the flavor of sheep meat. Unlike direct microbial fermentation, this method involves several stages, such as salt curing, drying, and ripening, which can promote lipid oxidation. During the processing of ham at varying temperature and humidity conditions, the IMF content decreased from 22.33 % in green ham to 5.43 % in the final product, while the contents of volatiles increased. Notably, dry-cured ham contained compounds, such as glutaraldehyde, hexanal, and heptanal, which contributed to a sweet and fruity aroma, and alcohols that endow hams with cheesy, nutty, and salty notes (Guo et al., 2019).

4.1.4. Packaging

The impact of packaging on the aroma of sheep meat is primarily associated with the gas composition within the packaging environment. The effects of different packaging methods on the aroma and flavor scores of sheep meat have been reported. Vacuum packaging and gas-conditioned packaging (80 % N_2 + 20 % CO_2) at 4 °C extended the storage duration of Kamieniec sheep LTL muscle. During the study spanning 0 to 30 days of storage, sensory evaluation revealed that the meat exhibited its highest aroma intensity on the 10th day (Zabek et al., 2021). For instance, vacuum packaging with 20 % CO_2 and 80 % N_2 outperformed high oxygen (HiOx-MAP) packaging with 80 % O_2 and 20 % CO_2. This study simulated different cold chain conditions for transporting meat to overseas retail markets. LT muscle of sheep meat was stored at −1.5 °C for 9 weeks, followed by display under light at 4 °C for 7 days. The aroma of LT muscle in HiOx-MAP packaging (rated 2.43) was lower (with a rating of >2.5 considered optimal) compared to the aroma of LT muscle from CO_2-MAP packaging (rated 2.57) ($P = 0.004$) (Kim et al., 2013). Hence, different packaging methods can lead to varying degrees of lipid oxidation due to differences in the gases used, ultimately affecting the flavor of sheep meat.

4.2. Thermal processing

The generation of volatile compounds in processed meat products primarily occurs during thermal processing, which encompasses techniques such as frying, deep-frying, baking, boiling, and other methods leading to lipid thermal degradation reactions, ultimately producing lipid-derived compounds. As summarized in Table 4, various factors, such as processing duration, processing method, specific cut, equipment, and the incorporation of natural additives can all influence the volatile profile of sheep and goat meat, consequently altering the flavor profile.

4.2.1. Thermal processing time and temperature

Since raw and cooked sheep meat contain essentially the same volatile flavor compounds but in different concentrations, and thermal processing methods are needed to facilitate the release of flavor compounds from the sheep meat, these differences may not become apparent until later phase in the process. When back strap muscles of small-tailed Han sheep × Mongolian sheep were roasted using the traditional charcoal method for 0, 2.5, 5, 7.5, 10, and 15 min, it was found that 10 min was the optimal roasting time based on sensory evaluation. At this time, core and surface temperatures of the back strap muscle were 78.4–80.5 °C and 86.3–96.5 °C, respectively. Therefore, the concentration of volatile flavor compounds (e.g., 1-octen-3-ol, nonanal, and hexanal) in the roasted lamb meat changed significantly after only 10 min (Liu, Hou, et al., 2022; Liu, Hui, et al., 2022; Liu, Li, et al., 2022). Furthermore, disparities in the concentrations of volatile compounds during electric roasting were shown to be lower compared to charcoal roasting. Wang, Han, et al., 2022; Wang, Li, et al., 2022; Wang, Luo, & Wang, 2022; Wang, Zhao, et al., 2022 electrically roasted the hind leg of Tam sheep and found that the highest concentrations of hexanal and 1-octen-3-ol were found in samples taken between 2 and 8 min. Only in samples electrically roasted for 20 min was it possible to differentiate between raw and electrically roasted meat by the concentration of volatile compounds. This phenomenon may be attributed to factors, such as the low surface temperature of sheep under electric roasting conditions, the relatively confined space in contact with air, and the higher moisture content in the air. Moreover, volatile compounds were less abundant in sheep subjected to electric roasting compared to the traditional charcoal roasting process, indicating that roasting temperature, environmental conditions, and the roasting method employed have a notable influence on the volatile flavor compounds in meat (Liu, Hou, et al., 2022; Liu, Hui, et al., 2022; Liu, Li, et al., 2022).

4.2.2. Processing methods

The aroma profiles of sheep meat can significantly differ based on the specific thermal processing methods employed. Liu et al. (2023) reported that Black Tibetan sheep were subjected to four distinct thermal treatments, including frying, deep-frying, roasting, and boiling. It has been shown that pan-frying and deep-frying resulted in notably higher aroma scores (17.00 and 16.10) and a more diverse range of volatile compounds in comparison to roasting and boiling (15.20 and 12.90). Notably, pan-frying demonstrated the highest aroma scores, primarily

Table 4
Effects of thermal processing (cooking) on the flavor of sheep and goat meat.

Species	Muscle type (cut)	Processing method	Results	References
Black Tibetan Sheep	Hind leg meat	• Pan-frying (226–228 °C for 3 min) • Deep-frying (226–228 °C for 4 min) • Baking (180 °C for 20 min) • Boiling (2.5 L boiling water for 60 min)	• Pan-fried meat contained the highest amounts of monounsaturated fatty acid (MUFA) and polyunsaturated fatty acid (PUFA), such as oleic, linoleic, and α-linolenic acids. • Aldehydes were the key aroma compounds in pan-fried meat. • The most PUFA in stir-frying sheep meat was linoleic acid, and the least was docosahexaenoic acid.	(Liu et al., 2023)
Tan sheep	Hind leg meat	• Industrial stir-frying mutton sao zi (80 °C for 0–35 min)	• 4-Nonanol and 2,3-dimethyl-2,3-butanediol were only observed in the stir-fried sample for 0–10 min at a low temperature stage. • For 15-min treatment, aldehyde was highest; for the last 10 min, hexanal was highest.	(Bai et al., 2021)
Tan sheep	Hind leg meat	• Electric roasting (roasting for 0–20 min)	• The highest concentrations of hexanal and 1-octen-3-ol were found in samples roasted for 2 to 8 min. • Meat roasted for 20 min can be distinguished by the concentration of volatile compounds.	(Wang, Luo, & Wang, 2022)
Small-tail sheep × Mongolian sheep	Sheep brisket (SBT), sheep loin (SLN), sheep rib (SR) and sheep leg (SLG)	• Stewing (boiler heating for 2 h)	• SLN showed the strongest intensity in fatty and delicate fragrance attributes. • SBT, SR and SLG had higher scores for roasting attribute.	(Qi et al., 2023)
Tamarix Sheep	Silversides	• Charcoal roasting and electric roasting (500–550 °C for 0–8 min)	• Charcoal-roasted sheep had higher contents of alcohols, aldehydes, ketones, alkanes, and aromatics, while the electric had higher contents of nitrogen oxides, terpenes, aromatics, and organic sulfur. • At 2 min, both taste and odor of charcoal and electric-roasted sheep were close to each other.	(Xu et al., 2021)
Small-tail sheep × Mongolian sheep	*Back strap* muscle	• Roasting for 0–15 min (core temperature and surface temperature were 78.4–80.5 °C and 86.3–96.5 °C)	• Hexanal, heptanal and 1-octen-3-ol are characteristic odors in roasted sheep.	(Liu, Hou, et al., 2022; Liu, Hui, et al., 2022; Liu, Li, et al., 2022)
Rambouillet sheep	Loin chop and leg	• Roasting loin chops at 232 °C • Roasting leg at 171 °C • 20 % ground juniper diet for 40 days	• The addition of 20 % juniper increased the contents of benzaldehyde, 1-heptanol, and 1-octanol concentrations and decreased decanal and nonenal concentrations in loin chop. • The 2-pentyl-furan concentrations were highest in leg roasts from 20 % juniper. • Yearling sheep fed 20 % juniper for up to 40 days with no negative impact on volatile compounds of meat.	(Kerth et al., 2019)
Small-tail sheep	Tenderloin	• Marination with blended cumin/zanthoxylum essential oil (BEO) for 30 min before heat 180 °C for 10 min	• The increased content of volatile organic compounds including cyclohexanone, ethyl acetate-D and linalool in blended cumin/zanthoxylum essential oil with ethyl acetate-D enriched the flavor of roasted mutton.	(Li, Tang, Yang, et al., 2023; Li, Zhao, Dai, et al., 2023; Li, Zhao, Jian, et al., 2023)
Boer goat	Hind leg meat	• Stewed mutton with 0.6 g thyme using different utensils contained casserole, wok, pressure cooker, and pressure-resistant bottle (stewed for 1 h after boiling)	• Different utensils had little effect on the aroma profile of stewed mutton with thyme. • Nonanal, (E)-2-octenal, and (E,E)-2,4-decadienal had the greatest contribution to the aroma profile of stewed mutton with thyme.	(Qi et al., 2022)
Saanen goat	Leg	• Marination of goat meat using juices (ginger and pineapple) and 0, 1, 3, 5 % sodium bicarbonate (SB) • Roasting at 180 °C for 6 min	• The meat marinated with pineapple juice for 60 min and then marinated with barbecue sauce containing 3 % SB for 60 min had the highest sensory score.	(Kaewthong et al., 2020)

characterized by the presence of aldehydes, which substantially contributed to a fat-like and umami aroma profile (Liu et al., 2023). Xu et al. (2021) reported that electric roasting led to a reduction in the number and concentration of various volatile markers, particularly aldehydes, alcohols, and ketones. For instance, the content of 3,2-octanedione, a compound responsible for a sweet and buttery flavor that significantly impacts the overall flavor of sheep meat, decreased when compared to the results obtained from charcoal roasting. Therefore, effective processing methods of sheep meat can enhance its flavor.

4.2.3. Processing vessel and natural additives

Stewing goat meat using various containers was observed to have a minimal impact on goat aroma. When Boer goat meat was stewed for an hour using different vessels (casserole, wok, pressure cooker, and pressure-resistant bottle), along with 3 g of salt and 0.6 g of thyme (*Thymus vulgaris L.*), there was no significant variation in aroma compounds among the vessels. Notably, nonanaldehyde, (E)-2-octanal, and (E,E)-2,4-decenal emerged as the key aroma compounds contributing to the overall aroma of thyme-stewed goat meat. This suggested that the choice of stewing vessel exerts a limited impact on aroma, with the primary influence stemming from the ingredients and spices used in the preparation (Qi et al., 2022). Consequently, the utilization of natural additives can significantly influence the flavor of sheep meat.

Natural additives, such as cumin (*Cuminum cyminum*) essential oil, Zanthoxylum essential oil, and blended cumin/zanthoxylum essential oil, have been utilized to enhance both the flavor and shelf life of thermally processed sheep meat. These oils were applied to the surface of sheep meat tenderloin, marinated over four stages (1, 2, 3, and 4 days) for 30 min, and then heated at 180 °C for 10 min. The effect of blended cumin/zanthoxylum essential oil on increasing the contents of volatile compounds was more pronounced. Notably, the presence of cyclohexanone, ethyl acetate D, and linalool, known for their antimicrobial and antioxidant properties, contributed to the enriched flavor of roasted sheep meat (Li, Tang, Yang, et al., 2023; Li, Zhao, Dai, et al., 2023; Li, Zhao, Jian, et al., 2023). Roasted Saanen goat meat marinated first in pineapple juice for 60 min and then with barbecue sauce containing 3 % sodium bicarbonate for 60 min achieved the highest score of 7.8 out of a possible sensory attribute score of 9 points, suggesting that the process improved flavor and enhanced consumer acceptability (Kaewthong et al., 2020). Consequently, the addition of spices to thermally processed sheep and goat meat not only mitigates undesired flavors but also enhances the overall flavor, which is the most direct way to improve the flavor of sheep and goat meat.

5. Conclusions and future perspectives

The flavor formation of sheep and goat meat can be influenced by a combination of several factors, including influences in IMF (especially phospholipids), lipid and FA content through pre-mortem and post-mortem factors, which further lead to changes in volatile flavor compounds ultimately affecting flavor formation. Pre-mortem factors, such as feeding practices and feed composition, can affect IMF content during sheep and goat growth, which is closely related to rumen microorganisms. Post-mortem factors, such as non-thermal processing (chilling, freezing, packaging, etc.) as well as thermal processing, can also affect the degree of lipid oxidation and the stability of volatile flavor compounds. This review provides recommendations for meat producers or processors on how to optimize pre- and post-mortem conditions to enhance meat flavor, making these strategies more actionable. Optimizing these factors can contribute to enhancing the flavor quality and meeting consumer demand for high-quality sheep and goat meat. Nevertheless, further in-depth studies on the relationship between these factors are needed in the future to provide more scientific support for the sustainable development of the sheep and goat meat industry.

i. There is a dearth of studies on the effect of rumen and gut microorganisms in ruminants on the flavor of sheep and goat meat. Most of these studies have focused on the effect of rumen microorganisms on the flavor of sheep and goat meat, while few have focused on intestinal microorganisms. Even so, the specific mechanisms by which rumen microbes affect flavor have not been fully elucidated. Therefore, it is particularly important to investigate the mechanisms by which gut microbes and rumen microbes co-regulate the flavor of sheep and goat meat. In order to fully understand this process, it is possible to combine Metagenomic/16S sequencing, metabolomic, proteomic, and transcriptomic multi-omics of rumen and intestinal combined flavor of sheep and goat meat, revealing the integrated regulatory mechanisms affecting the flavor of IMF.

ii. The effect of thermal processing on the flavor of sheep and goat meat is biased towards the study of individual factors. The combined effects of multiple factors, such as processing method, temperature, time, ingredients, and seasonings, are important in our comprehensive understanding of all key factors affecting the flavor of sheep and goat meat. Similarly, different seasonings with sheep and goat meat can be mixed and reacted at different temperatures and times to analyze the changes in the flavor components in sheep and goat meat samples. Furthermore, two-dimensional gas chromatography mass spectrometry (GC × GC–MS), comprehensive two-dimensional gas chromatography coupled to time-of-flight mass spectrometry (GC × GC-TOF-MS), gas chromatography-ion mobility spectrometry (GC-IMS), and GC-olfactometry (GC-O) are robust in revealing the molecular mechanisms responsible for the effect of thermal processing on the flavor of sheep and goat meat.

iii. The study on meat flavor needs a more comprehensive integration of omics technologies. Employing foodomics coupled with lipidomics to analyze meat flavor can further elucidate its complexity. Foodomics enables the characterization and quantification of biomacromolecules in meat and correlates this information with the composition of lipid molecules, thereby delineating the impact of lipid components on flavor. Investigating how lipidomics influences meat flavor properties provides a deeper understanding of the molecular mechanisms underlying the effects of both non-thermal and thermal processing on the flavor of sheep and goat meat.

CRediT authorship contribution statement

Tianyu Su: Writing – original draft. **Yu Fu:** Writing – original draft. **Jingjie Tan:** Writing – review & editing. **Mohammed Gagaoua:** Writing – review & editing. **Kathrine H. Bak:** Writing – review & editing. **Olugbenga P. Soladoye:** Writing – review & editing. **Zhongquan Zhao:** Writing – review & editing. **Yongju Zhao:** Writing – review & editing. **Wei Wu:** Writing – review & editing, Supervision, Funding acquisition.

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.

Data availability

No data was used for the research described in the article.

Acknowledgments

The authors gratefully acknowledge the financial support by National Natural Science Foundation of China (32001766), Natural Science Foundation of Chongqing (cstc2021jcyj-msxmX1014), Fundamental Research Funds for the Central Universities of China (SWU-KQ22023), Chongqing Modern Agricultural Industry Technology System (CQMAITS202413), and the Collection, Utilization and Innovation of Germplasm Resources by Research Institutes and Enterprises of

Chongqing, China (cqnyncw-kqlhtxm).

References

Arshad, M. S., Sohaib, M., Ahmad, R. S., Nadeem, M. T., Imran, A., Arshad, M. U., … Amjad, Z. (2018). Ruminant meat flavor influenced by different factors with special reference to fatty acids. *Lipids in Health and Disease, 17*, 1–13.

Asadollahi, S., Sari, M., Erafanimajd, N., Kiani, A., & Ponnampalam, E. N. (2017). Supplementation of sugar beet pulp and roasted canola seed in a concentrate diet altered carcass traits, muscle (longissimus dorsi) composition and meat sensory properties of Arabian fattening lambs. *Small Ruminant Research, 153*, 95–102.

Aung, S. H., Abeyrathne, E., Hossain, M. A., Jung, D. Y., Kim, H. C., Jo, C., & Nam, K. C. (2023). Comparative quality traits, flavor compounds, and metabolite profile of Korean native black goat meat. *Food Science of Animal Resources, 43*(4), 639–658.

Babiker, S. A., Elkhider, I. A., & Shafie, S. A. (1990). Chemical-composition and quality attributes of goat meat and lamb. *Meat Science, 28*(4), 273–277.

Bai, S., Wang, Y. R., Luo, R. M., Ding, D., Bai, H., & Shen, F. (2021). Characterization of flavor volatile compounds in industrial stir-frying mutton sao zi by GC-MS, E-nose, and physicochemical analysis. *Food Science & Nutrition, 9*(1), 499–513.

Bleicher, J., Ebner, E. E., & Bak, K. H. (2022). Formation and analysis of volatile and odor compounds in meat-A review. *Molecules, 27*(19), 6703.

Brand, T. S., Van Der Merwe, D. A., Hoffman, L. C., & Geldenhuys, G. (2018). The effect of dietary energy content on quality characteristics of Boer goat meat. *Meat Science, 139*, 74–81.

Bravo-Lamas, L., Barron, L. J. R., Farmer, L., & Aldai, N. (2018). Fatty acid composition of intramuscular fat and odour-active compounds of lamb commercialized in northern Spain. *Meat Science, 139*, 231–238.

Buccioni, A., Decandia, M., Minieri, S., Molle, G., & Cabiddu, A. (2012). Lipid metabolism in the rumen: New insights on lipolysis and biohydrogenation with an emphasis on the role of endogenous plant factors. *Animal Feed Science and Technology, 174*(1–2), 1–25.

Calkins, C. R., & Hodgen, J. M. (2007). A fresh look at meat flavor. *Meat Science, 77*(1), 63–80.

Cha, J. Y., Han, J., Heo, J., Yu, H. H., Kim, Y.-J., Jang, H. W., … Choi, Y.-S. (2024). Variation of volatile compounds and sensory profile for Protaetia brevitarsis larvae fermented with lactic acid bacteria and yeast. *Food Chemistry, 452*, Article 139480.

Chang, L., Niu, X., Huang, S., Song, D., Ran, X., & Wang, J. (2024). Detection of structural variants linked to mutton flavor and odor in two closely related black goat breeds. *BMC Genomics, 25*(1), 979.

Cheng, J. B., Zhang, X. X., Xu, D., Zhang, D. Y., Zhang, Y. K., Song, Q. Z., … Wang, W. M. (2022). Relationship between rumen microbial differences and traits among Hu sheep, Tan sheep, and Dorper sheep. *Journal of Animal Science, 100*(9), Article skac261.

Del Bianco, S., Natalello, A., Luciano, G., Valenti, B., Campidonico, L., Gkarane, V., … Piasentier, E. (2021). Influence of dietary inclusion of tannin extracts from mimosa, chestnut and tara on volatile compounds and flavour in lamb meat. *Meat Science, 172*, Article 108336.

Dias Junior Paulo Cesar, G., Dos Santos, I. J., Do Nascimento, F. L., Paternina, E. A. S., Alves, B. A., Pereira, I. G., … Furusho-Garcia, I. F. (2022). Macadamia oil and vitamin E for lambs: Performance, blood parameters, meat quality, fatty acid profile and gene expression. *Animal Feed Science and Technology, 293*, Article 115475.

Diogenes, L. V., Oliveira, R. L., Souza, M. N. S., Mazza, P. H. S., Junior, J. M. D., Pereira, E. S., … de Oliveira, J. P. F. (2022). Effect of dietary Buriti oil on the quality, fatty acid profile and sensorial attributes of lamb meat. *Meat Science, 186*, Article 108734.

Dominguez, R., Pateiro, M., Gagaoua, M., Barba, F. J., Zhang, W. G., & Lorenzo, J. M. (2019). A comprehensive review on lipid oxidation in meat and meat products. *Antioxidants, 8*(10), 429.

Dou, L., Jin, Y., Li, H. J., Liu, C., Yang, Z. H., Chen, X. Y., & Su, L. (2023). Effect of feeding system on muscle fiber composition, antioxidant capacity, and nutritional and organoleptic traits of goat meat. *Animals, 13*(1), 172.

Dou, L., Liu, C., Yang, Z. H., Su, R. N., Chen, X. Y., Hou, Y. R., … Jin, Y. (2022). Effects of oxidative stability variation on lamb meat quality and flavor during postmortem aging. *Journal of Food Science, 87*(6), 2578–2594.

Echegaray, N., Dominguez, R., Bodas, R., Montanes, M., Garcia, J. J., Benito, A., … Lorenzo, J. M. (2021). Characterization of volatile profile of longissimus thoracis et lumborum muscle from Castellana and INRA 401 lambs reared under commercial conditions. *Small Ruminant Research, 200*, Article 106396.

Echegaray, N., Dominguez, R., Cadavez, V. A. P., Bermudez, R., Purrinos, L., Gonzales-Barron, U., … Lorenzo, J. M. (2021). Influence of the production system (intensive vs. extensive) at farm level on proximate composition and volatile compounds of portuguese lamb meat. *Foods, 10*(7).

Erol, H., & Unal, N. (2022). Meat production traits of angora goats. 2. Meat quality characteristics and fatty acid composition of meat from intact and castrated kids. *Animal Production Science, 62*(16), 1607–1617.

Fu, Y. H., Cao, S. Y., Yang, L., & Li, Z. L. (2022). Flavor formation based on lipid in meat and meat products: A review. *Journal of Food Biochemistry, 46*(12), Article e14439.

Gasior, R., Kawecka, A., Wojtycza, K., & Sikora, J. (2021). Composition of volatile compounds in heat-treated meat from polish native sheep breeds using hs-spme-gc/ms - chemometric classification based on breed and age. *Annals of Animal Science, 21*(1), 331–346.

Gunawan, A., Jakaria Listyarini, K., Furqon, A., Sumantri, C., Akter, S. H., & Uddin, M. J. (2018). Transcriptome signature of liver tissue with divergent mutton odour and flavour using RNA deep sequencing. *Gene, 676*, 86–94.

Guo, X., Lu, S. L., Wang, Y. Q., Dong, J., Ji, H., & Wang, Q. L. (2019). Correlations among flavor compounds, lipid oxidation indices, and endogenous enzyme activity during the processing of Xinjiang dry-cured mutton ham. *Journal of Food Processing and Preservation, 43*(11), Article e14199.

Halli, K., Bohlouli, M., Schulz, L., Sundrum, A., & König, S. (2022). Estimation of direct and maternal genetic effects and annotation of potential candidate genes for weight and meat quality traits in a genotyped outdoor dual-purpose cattle breed. *Translational Animal Science, 6*(1).

Hastie, M., Torrico, D., Li, Z. Z., Ha, M., & Warner, R. (2022). Consumer characterization of wet- and dry-aged mutton flavor profile using check-all-that-apply. *Foods, 11*(20), 3167.

He, X. N., Wang, H. B., Yang, X. L., Xi, B., Li, W. H., Wang, F., … Gao, Y. Q. (2022). The effects of frozen storage on fatty acids, amino acids, and volatile compounds in mutton stored for 90 days. *Journal of Food Processing and Preservation, 46*(5), Article e16518.

Hocquette, J. F., Gondret, F., Baeza, E., Medale, F., Jurie, C., & Pethick, D. W. (2010). Intramuscular fat content in meat-producing animals: Development, genetic and nutritional control, and identification of putative markers. *Animal, 4*(2), 303–319.

Insausti, K., Murillo-Arbizu, M. T., Urrutia, O., Mendizabal, J. A., Beriain, M. J., Colle, M. J., … Arana, A. (2021). Volatile compounds, odour and flavour attributes of lamb meat from the Navarra breed as affected by ageing. *Foods, 10*(3), 493.

Jaborek, J. R., Zerby, H. N., Wick, M. P., Fluharty, F. L., & Moeller, S. J. (2020). Effect of energy source and level, animal age, and sex on the flavor profile of sheep meat. *Translational Animal Science, 4*(2), 1140–1147.

Janíček, M., Volna, D., Repkovský, M., & Margetín, M. (2021). Effect of weaning and sex on meat fatty acid profile of grazing lambs. *Acta Fytotechnica et Zootechnica, 24*, 25–28.

Jia, W., Shi, Q., & Shi, L. (2021). Effect of irradiation treatment on the lipid composition and nutritional quality of goat meat. *Food Chemistry, 351*, Article 129295.

Jiang, L., Mu, Y., Su, W., Tian, H., Zhao, M., Su, G., & Zhao, C. (2023). Effects of *Pediococcus acidilactici* and Rhizopus Oryzae on microbiota and metabolomic profiling in fermented dry-cure mutton sausages. *Food Chemistry, 403*, Article 134431.

Kaewthong, P., Wattanachant, C., & Wattanachant, S. (2020). Improving the quality of barbecued culled-dairy-goat meat by marination with plant juices and sodium bicarbonate. *Journal of Food Science and Technology, 58*, 333–342.

Kanokruangrong, S., Birch, E., & Bekhit, A. (2018). *Processing effects on meat flavor*. In.

Kawecka, A., & Pasternak, M. (2022). The effect of slaughter age on meat quality of male kids of the polish carpathian native goat breed. *Animals, 12*(6), 702.

Kearns, M., Ponnampalam, E. N., Jacquier, J. C., Grasso, S., Boland, T. M., Sheridan, H., & Monahan, F. J. (2023). Can botanically-diverse pastures positively impact the nutritional and antioxidant composition of ruminant meat? – Invited review. *Meat Science, 197*, Article 109055.

Kerth, C. R., Wall, K. R., Miller, R. K., Whitney, T. R., Stewart, W. C., Boles, J. A., & Murphy, T. W. (2019). Effects of feeding juniper as a roughage on feedlot performance, carcass measurements, meat sensory attributes, and volatile aroma compounds of yearling Rambouillet wethers. *Journal of Animal Science, 97*(7), 2850–2864.

Kerth, C. R., Wall, K. R., Smith, S. B., Whitney, T. R., Glasscock, J. L., & Sawyer, J. T. (2018). Substituting ground woody plants for cottonseed hulls in lamb feedlot diets: Carcass characteristics, adipose tissue fatty acid composition, and sensory panel traits. *Journal of Animal Science, 96*(2), 487–497.

Khan, M. I., Jo, C., & Tariq, M. R. (2015). Meat flavor precursors and factors influencing flavor precursors-A systematic review. *Meat Science, 110*, 278–284.

Kim, Y. H. B., Stuart, A., Rosenvold, K., & Maclennan, G. (2013). Effect of forage and retail packaging types on meat quality of long-term chilled lamb loins. *Journal of Animal Science, 91*(12), 5998–6007.

Klupsaite, D., Buckiuniene, V., Bliznikas, S., Sidlauskiene, S., Dauksiene, A., Klementaviciute, J., … Bartkiene, E. (2022). Impact of Romanov breed lamb gender on carcass traits and meat quality parameters including biogenic amines and malondialdehyde changes during storage. *Food Science & Nutrition, 10*(6), 1745–1755.

Li, H. B., Zhao, L. L., Dai, Q. Y., Mo, H. Z., Liu, Z. B., Pu, H. Y., … Hu, L. B. (2023). Blended cumin/Zanthoxylum essential oil improve the antibacterial, fresh-keeping performance and flavor of chilled fresh mutton. *Meat Science, 200*, Article 109173.

Li, J., Tang, C. H., Yang, Y. Y., Hu, Y., Zhao, Q. Y., Ma, Q., … Zhang, J. M. (2023). Characterization of meat quality traits, fatty acids and volatile compounds in Hu and Tan sheep. *Frontiers in Nutrition, 10*, Article 1072159.

Li, J., Tang, C. H., Zhao, Q. Y., Yang, Y. Y., Li, F. D., Qin, Y. C., … Zhang, J. M. (2020). Integrated lipidomics and targeted metabolomics analyses reveal changes in flavor precursors in psoas major muscle of castrated lambs. *Food Chemistry, 333*, Article 127451.

Li, J., Yang, Y. Y., Tang, C. H., Yue, S. N., Zhao, Q. Y., Li, F. D., & Zhang, J. M. (2022). Changes in lipids and aroma compounds in intramuscular fat from Hu sheep. *Food Chemistry, 383*, Article 132611.

Li, Z., Zhao, X. A., Jian, L. Y., Wang, B., & Luo, H. L. (2023). Rumen microbial-driven metabolite from grazing lambs potentially regulates body fatty acid metabolism by lipid-related genes in liver. *Journal of Animal Science and Biotechnology, 14*(1), 39.

Listrat, A., Lebret, B., Louveau, I., Astruc, T., Bonnet, M., Lefaucheur, L., … Bugeon, J. (2016). How muscle structure and composition influence meat and flesh quality. *The Scientifi cWorld Journal, 2016*, 3182746.

Liu, C., Hou, Y. R., Su, R. N., Luo, Y. L., Dou, L., Yang, Z. H., … Jin, Y. (2022). Effect of dietary probiotics supplementation on meat quality, volatile flavor compounds, muscle fiber characteristics, and antioxidant capacity in lambs. *Food Science & Nutrition, 10*(8), 2646–2658.

Liu, D. Y., Zhou, G. H., & Xu, X. L. (2008). "ROAV" method: A new method for determining key odor compounds of Rugao ham. *Food Science, 29*(7), 370–374.

Liu, H., Hui, T., Zheng, X. C., Li, S. B., Wei, X. R., Li, P., … Wang, Z. Y. (2022). Characterization of key lipids for binding and generating aroma compounds in roasted mutton by UPLC-ESI-MS/MS and Orbitrap Exploris GC. *Food Chemistry, 374*, Article 131723.

Liu, J. Q., Han, L. J., Han, W. Z., Gui, L. S., Yuan, Z. Z., Hou, S. Z., … Alanazi, A. M. (2023). Effect of different heat treatments on the quality and flavor compounds of black Tibetan sheep meat by HS-GC-IMS coupled with multivariate analysis. *Molecules, 28*(1), 165.

Liu, W. J., Ding, H., Erdene, K., Chen, R. W., Mu, Q. E., & Ao, C. J. (2019). Effects of flavonoids from Allium mongolicum regel as a dietary additive on meat quality and composition of fatty acids related to flavor in lambs. *Canadian Journal of Animal Science, 99*(1), 15–23.

Liu, Y. N., Li, R. H., Ying, Y., Zhang, Y. D., Huang, Y. Y., Wu, H. X., & Lin, K. J. (2022). Non-genetic factors affecting the meat quality and flavor of inner Mongolian lambs: A review. *Frontiers in Veterinary Science, 9*, Article 1067880.

Lu, Z. K., Yue, Y. J., Shi, H. A., Zhang, J. X., Liu, T. G., Liu, J. B., & Yang, B. H. (2022). Effects of sheep sires on muscle Fiber characteristics, fatty acid composition and volatile flavor compounds in F-1 crossbred lambs. *Foods, 11*(24), 4076.

Luo, Y. L., Wang, B. H., Liu, C., Su, R. N., Hou, Y. R., Yao, D., … Jin, Y. (2019). Meat quality, fatty acids, volatile compounds, and antioxidant properties of lambs fed pasture versus mixed diet. *Food Science & Nutrition, 7*(9), 2796–2805.

Ma, Y., Han, L., Raza, S. H. A., Gui, L., Zhang, X., Hou, S., … Alkhalil, S. S. (2023). Exploring the effects of palm kernel meal feeding on the meat quality and rumen microorganisms of Qinghai Tibetan sheep. *Food Science & Nutrition, 11*(6), 3516–3534.

Madruga, M., Dantas, I., Queiroz, A., Brasil, L., & Ishihara, Y. (2013). Volatiles and water- and fat-soluble precursors of Saanen goat and cross Suffolk lamb flavour. *Molecules, 18*(2), 2150–2165.

Madruga, M. S., Arruda, S. G. B., Narain, N., & Souza, J. G. (2000). Castration and slaughter age effects on panel assessment and aroma compounds of the "mestiço" goat meat. *Meat Science, 56*(2), 117–125.

Miguel, E., Blázquez, B., & Ruiz de Huidobro, F. R. (2021a). Liveweight and sex effects on instrumental meat quality of rubia de el molar autochthonous ovine breed. *Animals, 11*(5), 1323.

Miguel, E., Blázquez, B., & Ruiz de Huidobro, F. R. (2021b). Live weight and sex effects on sensory quality of Rubia de El molar autochthonous ovine breed meat. *Animals, 11*(5), 1293.

Natalello, A., Menci, R., Luciano, G., Monahan, F., Gravador, R. S., Valenti, B., … Priolo, A. (2023). Effect of dietary pomegranate by-product on lamb flavour. *Meat Science, 198*, Article 109118.

Nobre, P. T., Munekata, P. E. S., Costa, R. G., Carvalho, F. R., Ribeiro, N. L., Queiroga, R., … Lorenzo, J. M. (2020). The impact of dietary supplementation with guava (*Psidium guajava* L.) agroindustrial waste on growth performance and meat quality of lambs. *Meat Science, 164*, Article 108105.

Parente, M. D. M., Rocha, K. S., Bessa, R. J. B., Parente, H. N., Zanine, A. D., Machado, N. A. F., … Alves, S. P. (2020). Effects of the dietary inclusion of babassu oil or Buriti oil on lamb performance, meat quality and fatty acid composition. *Meat Science, 160*, Article 107971.

Pavan, E., McCoard, S. A., Agnew, M., Zhang, R., Taukiri, K., Farouk, M. M., & Realini, C. E. (2022). Effects of dairy lambs'rearing system and slaughter age on consumer liking of lamb meat and its association with lipid content and composition. *11*(15), 2350.

Pavan, E., Subbaraj, A. K., Eyres, G. T., Silcock, P., & Realini, C. E. (2022). Association of metabolomic and lipidomic data with Chinese and New Zealand consumer clusters showing preferential likings for lamb meat from three production systems. *Food Research International, 158*, Article 111504.

Ponnampalam, E. N., Priyashantha, H., Vidanarachchi, J. K., Kiani, A., & Holman, B. W. B. (2024). Effects of nutritional factors on fat content, fatty acid composition, and sensorial properties of meat and Milk from domesticated ruminants: An overview. *Animals, 14*, 840.

Qi, N., Liu, R. J., Sun, J., Chen, H. T., & Zhang, N. (2023). Characterizing key aroma-active compounds of stewed mutton using gas chromatography-olfactometry-mass spectrometry coupled with odour activity value. *Flavour and Fragrance Journal, 38*(4), 263–273.

Qi, S. S., Wang, P., Zhan, P., & Tian, H. L. (2022). Characterization of key aroma compounds in stewed mutton (goat meat) added with thyme (*Thymus vulgaris* L.) based on the combination of instrumental analysis and sensory verification. *Food Chemistry, 371*, Article 131111.

Realini, C. E., Pavan, E., Johnson, P. L., Font-I-Furnols, M., Jacob, N., Agnew, M., … Moon, C. D. (2021). Consumer liking of *M. longissimus* lumborum from New Zealand pasture-finished lamb is influenced by intramuscular fat. *Meat Science, 173*, Article 108380.

Realini, C. E., Pavan, E., Purchas, R. W., Agnew, M., Johnson, P. L., Bermingham, E. N., & Moon, C. D. (2021). Relationships between intramuscular fat percentage and fatty acid composition in *M. longissimus* lumborum of pasture-finished lambs in New Zealand. *Meat Science, 181*, Article 108618.

Schonfeldt, H. C., Naude, R. T., Bok, W., Vanheerden, S. M., Smit, R., & Boshoff, E. (1993). Flavor-related and tenderness-related quality characteristics of goat and sheep meat. *Meat Science, 34*(3), 363–379.

Sgarro, M. F., Maggiolino, A., Pateiro, M., Dominguez, R., Iannaccone, F., De Palo, P., & Lorenzo, J. M. (2022). Effects of anthocyanin supplementation and ageing time on the volatile organic compounds and sensory attributes of meat from goat kids. *Animals, 12*(2), 139.

Sha, Y., He, Y., Liu, X., Shao, P., Wang, F., Xie, Z., … Chen, G. (2023). Interactions of rumen microbiota and metabolites with meat quality-related genes to regulate meat quality and flavor of Tibetan sheep under nutrient stress in the cold season. *Journal of Applied Microbiology, 134*(8), Article lxad182.

Smeti, S., Yagoubi, Y., Srihi, H., Lobon, S., Bertolin, J. R., Mahouachi, M., … Atti, N. (2021). Effects of using rosemary residues as a cereal substitute in concentrate on vitamin E, antioxidant activity, color, lipid oxidation, and fatty acid profile of Barbarine lamb meat. *Animals, 11*(7), 2100.

Sohail, A., Al-Dalali, S., Wang, J. A., Xie, J. C., Shakoor, A., Asimi, S., … Patil, P. (2022). Aroma compounds identified in cooked meat: A review. *Food Research International, 157*, Article 111385.

Teixeira, A., Silva, S., Guedes, C., & Rodrigues, S. (2020). Sheep and goat meat processed products quality: A review. *Foods, 9*(7), 960.

Tian, X. Z., Lu, Q., Zhao, S. G., Li, J. X., Luo, Q. Y., Wang, X., … Zheng, N. (2021). Purple corn anthocyanin affects lipid mechanism, flavor compound profiles, and related gene expression of longissimus Thoracis et Lumborum muscle in goats. *Animals, 11*(8), 2407.

Tibaoui, S., Smeti, S., Essid, I., Bertolin, J. R., Joy, M., & Atti, N. (2020). Physicochemical characteristics, fatty acid profile, alpha-tocopherol content, and lipid oxidation of meat from ewes fed different levels of distilled Myrtle residues. *Molecules, 25*(21), 4975.

Tsitsos, A., Economou, V., Chouliara, E., Ambrosiadis, I., & Arsenos, G. (2022). A comparative study on microbiological and chemical characteristics of small ruminant carcasses from abattoirs in Greece. *Foods, 11*(15), 2370.

Wang, B., Wang, Y. J., Zuo, S. X., Peng, S. J., Wang, Z. J., Zhang, Y. J., & Luo, H. L. (2021). Untargeted and targeted metabolomics profiling of muscle reveals enhanced meat quality in artificial pasture grazing Tan lambs via rescheduling the rumen bacterial community. *Journal of Agricultural and Food Chemistry, 69*(2), 846–858.

Wang, B., Wang, Z. Z., Chen, Y., Liu, X. L., Liu, K., Zhang, Y. J., & Luo, H. L. (2021). Carcass traits, meat quality, and volatile compounds of lamb meat from different restricted grazing time and indoor supplementary feeding systems. *Foods, 10*(11), 2822.

Wang, B., Zhao, X. G., Zhang, B. Y., Cui, Y. M., Nueraihemaiti, M., Kou, Q. F., & Luo, H. L. (2022). Assessment of components related to flavor and taste in Tan-lamb meat under different silage-feeding regimens using integrative metabolomics. *Food Chemistry: X, 14*, Article 100269.

Wang, B. H., Luo, Y. L., Wang, Y., Wang, D. B., Hou, Y. R., Yao, D., … Jin, Y. (2021). Rumen bacteria and meat fatty acid composition of Sunit sheep reared under different feeding regimens in China. *Journal of the Science of Food and Agriculture, 101*(3), 1100–1110.

Wang, F., Gao, Y. Q., Wang, H. B., Xi, B., He, X. N., Yang, X. L., & Li, W. H. (2021). Analysis of volatile compounds and flavor fingerprint in Jingyuan lamb of different ages using gas chromatography-ion mobility spectrometry (GC-IMS). *Meat Science, 175*, Article 108449.

Wang, H. (2023). Production of the livestock sector: A 60-year review and outlook. In *China's food security: Strategies and countermeasures* (pp. 135–163). Springer Nature Singapore: Singapore.

Wang, J., Lu, R., Li, Y., Lu, J., Liang, Q., Zheng, Z., … Zeng, J. (2023). Dietary supplementation with jasmine flower residue improves meat quality and flavor of goat. *Frontiers in Nutrition, 10*, Article 1145841.

Wang, M. Y., Han, H. Q., Shang, Y., Zhang, L. Y., Zhang, Y., Su, C. A. Y., … Gao, T. Y. (2022). Effect of the replacement of maize silage and Soyabean meal with mulberry silage in the diet of Hu lambs on growth performance, serum biochemical indices, slaughter performance, and meat quality. *Animals, 12*(22), 1406.

Wang, W., Sun, B., Hu, P., Zhou, M., Sun, S., Du, P., … Wang, S. (2019). Comparison of differential flavor metabolites in meat of Lubei white goat, Jining gray goat and Boer goat. *Metabolites, 9*(9), 176.

Wang, Y. R., Luo, R. M., & Wang, S. L. (2022). Study on key aroma compounds in the electric roasting process of Tan mutton. *Journal of Food Processing and Preservation, 46*(11), Article e17095.

Wang, Y. Y., Li, T. F., Chen, X. Y., Liu, C. Y., Jin, X. M., Tan, H., & Long, M. X. (2022). Preliminary investigation of mixed orchard hays on the meat quality, fatty acid profile, and gastrointestinal microbiota in goat kids. *Animals, 12*(6), 780.

Watkins, P. J., & Frank, D. (2019). Heptadecanoic acid as an indicator of BCFA content in sheep fat. *Meat Science, 151*, 33–35.

Watkins, P. J., Frank, D., Singh, T. K., Young, O. A., & Warner, R. D. (2013). Sheepmeat flavor and the effect of different feeding systems: A review. *Journal of Agricultural and Food Chemistry, 61*(15), 3561–3579.

Wood, J. D., Richardson, R. I., Nute, G. R., Fisher, A. V., Campo, M. M., Kasapidou, E., … Enser, M. (2004). Effects of fatty acids on meat quality: A review. *Meat Science, 66*(1), 21–32.

Xu, L., Liu, C. Y., Li, S. B., Xu, J. R., Liu, H., Zheng, X. C., & Chen, L. (2023). Association of lipidome evolution with the corresponding volatile characteristics of postmortem lamb during chilled storage. *Food Research International, 169*, Article 112916.

Xu, Y. J., Zhang, D. Q., Chen, R. X., Yang, X. Y., Liu, H., Wang, Z. Y., & Hui, T. (2021). Comprehensive evaluation of flavor in charcoal and electric-roasted Tamarix lamb by HS-SPME/GC-MS combined with electronic tongue and electronic nose. *Foods, 10*(11), 2676.

Yang, Y. Y., Li, J., Jia, X. T., Zhao, Q. Y., Ma, Q., Yu, Y. A., … Zhang, J. M. (2022). Characterization of the flavor precursors and flavor fingerprints in grazing lambs by Foodomics. *Foods, 11*(2), 191.

Yang, Z. H., Liu, C., Dou, L., Chen, X. Y., Zhao, L. H., Su, L., & Jin, Y. (2022). Effects of feeding regimes and postmortem aging on meat quality, fatty acid composition, and volatile flavor of longissimus Thoracis muscle in Sunit sheep. *Animals, 12*(22), 3081.

Young, O. A., Lane, G. A., Priolo, A., & Fraser, K. (2003). Pastoral and species flavour in lambs raised on pasture, lucerne or maize. *Journal of the Science of Food and Agriculture, 83*(2), 93–104.

Yousefi, A. R., Sadeghipanah, A., Kohram, H., Shahneh, A. Z., Davachi, N. D., Aghashahi, A., & Ponnampalam, E. N. (2019). Determination of optimum carcass weight for meat quality and fatty acid composition in fat-tailed male and female Chall lambs. *Tropical Animal Health and Production, 51*(3), 545–553.

Yu, Y., Zhang, B., Jiang, X., Cui, Y., Luo, H., Stergiadis, S., & Wang, B. (2024). Exploring the metabolomic landscape: *Perilla frutescens* as a promising enhancer of production, flavor, and nutrition in Tan lamb meat. *Meat Science, 209*, Article 109419.

Zabek, K., Micinski, J., Milewski, S., & Sobczak, A. (2021). Effect of modified atmosphere packaging and vacuum packaging on quality characteristics of lamb meat. *Archives Animal Breeding, 64*(2), 437–445.

Zhang, C., Zhang, H., Liu, M., Zhao, X. G., & Luo, H. L. (2020). Effect of breed on the volatile compound precursors and odor profile attributes of lamb meat. *Foods, 9*(9), 1178.

Zhang, M., Zhang, Z., Zhang, X., Lu, C., Yang, W., Xie, X., … Jiao, P. (2024). Effects of dietary *Clostridium butyricum* and rumen protected fat on meat quality, oxidative stability, and chemical composition of finishing goats. *Journal of Animal Science and Biotechnology, 15*(1), 3.

Zhang, X., Han, L. J., Hou, S. Z., Raza, S. H. A., Gui, L. S., Sun, S. N., … Aloufi, B. H. (2022). Metabolomics approach reveals high energy diet improves the quality and enhances the flavor of black Tibetan sheep meat by altering the composition of rumen microbiota. *Frontiers in Nutrition, 9*, Article 915558.

Zhang, X. Y., Yuan, Z., Li, F., & Yue, X. (2022). Integrating transcriptome and metabolome to identify key genes regulating important muscular flavour precursors in sheep. *Animal, 16*(12), Article 100679.

Zhou, J. Y., Ying, Y. B., Peng, J. B., Su, P., Chen, J. C., & Hu, Y. Q. (2022). Lactic acid bacteria and *Staphylococcus carnosus* fermentation as a means for eliminating 4-alkyl branched odour fatty acids of mutton jerky and its effect on other quality characteristics. *International Journal of Food Science and Technology, 57*(10), 6843–6851.