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Review Article

Potential use of garlic products in ruminant feeding: A review

He Ding [a], Changjin Ao [b], Xiaoqing Zhang [a,*]

[a] Institute of Grassland Research, Chinese Academy of Agricultural Sciences, Hohhot 010010, China
[b] Key Laboratory of Animal Feed and Nutrition of Inner Mongolia Autonomous Region, College of Animal Science, Inner Mongolia Agricultural University, Hohhot 010018, China

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ABSTRACT

The addition of antibiotics as growth promoters to ruminant feed can result in bacterial resistance and antibiotic residues in ruminant products. Correspondingly, there is serious public concern regarding the presence of antibiotic residue in ruminant products and the consequent threat to human health. As a result, the addition of plants and their products to ruminant feeds, as an alternative to antibiotics, has received much attention recently. Garlic and its products are rich in organosulphur compounds, which have a variety of biological activities and have been widely used as natural additives in animal production. This review presents recent knowledge on the addition of garlic products (powder, skin, oil, leaf and extracts) to the diets of ruminants. In this paper, garlic products are evaluated with respect to their chemical composition, bioactive compounds, and their impacts on the rumen ecosystem, antioxidant status, immune response, parasitic infection, growth performance and product quality of ruminants. This review provides valuable guidance and a theoretical basis for the development of garlic products as green, highly efficient and safe additives, with the aims of promoting ruminant growth and health, reducing methane emissions and improving ruminant product quality. Garlic extracts have the potential to control parasite infections by decreasing the faecal egg count. Garlic powder, oil and allicin are able to reduce the methane emissions of ruminants. Organosulphur compounds such as allicin, which is present in garlic products, have the potential to inhibit membrane lipid synthesis of the archaeal community, thus influencing the population of methanogenic archaea and resulting in a reduction in methane emissions. Some garlic products are also able to increase the average daily gain (garlic skin, water extract, and leaf) and the feed conversion ratio (garlic skin and leaf) of ruminants. Garlic stalk silage fed to sheep has the potential to improve the nutritional value of mutton by increasing the concentrations of linoleic and linolenic acids and essential amino acids. Sheep fed a diet containing garlic powder or oil are able to produce milk with higher concentrations of the conjugated linoleic acids and n-3 fatty acids, which has health benefits for consumers, due to the widely recognized positive impact of n-3 polyunsaturated fatty acids and conjugated linoleic acids on human heart health, improving platelet aggregation, vasodilation and thrombotic tendency. Overall, garlic products have the potential to enhance growth performance and product quality and reduce parasite infections, as well as methane emissions of ruminants.

1. Introduction

The addition of antibiotics to animal feeds has been widely used to promote growth performance, the feed conversion rate, product quality and animal health (Ran et al., 2018; Wu et al., 2020). However, the long-term overuse of antibiotics can result in microbial resistance to drugs and antibiotic residue in edible animal products; this has attracted significant public concern due to the development of antibiotic resistance in humans (Do et al., 2019; Lan et al., 2020). Therefore, the use of antibiotics as growth promoters

* Corresponding author.
E-mail address: zhangxiaoqing@caas.cn (X. Zhang).
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in livestock has been prohibited in the European Union since 2006 (EC, 2003). Rumen ecology and ruminant growth performance and product quality are all influenced by diet. Thus, dietary supplementation is an effective and convenient method to manipulate the nutritional composition of the animal's diet in order to achieve better rumen ecology, growth performance and product quality. Plants and their products contain a variety of bioactive compounds that are responsible for all kinds of biological functions, and as such, are a suitable alternative to antibiotic supplementation in animal feed. Studies have shown that supplementation with plant products can improve animal performance, health and product quality (Tao et al., 2020).

Garlic (*Allium sativum* L.), native to Central and South Asia, is an annual bulbous herb of the *Alliaceae* family (Rouf et al., 2020). Approximately 27 million tonnes of garlic are produced worldwide each year, with China, India, South Korea, Egypt and the USA being the top five garlic-producing countries (Lee et al., 2020; Rouf et al., 2020). Garlic and its products are rich in bioactive organosulphur compounds such as allicin, allixin and allylsulfides, which give garlic products antimicrobial, antioxidant, anti-inflammatory, immunomodulatory, antihypertensive, cancer-preventive, anti-hyperlipidemic and other physiological properties (Qin et al., 2020). Thus, garlic is known worldwide as a “medicine and food homology” that is superior to traditional and alternative medicines (Liu et al., 2015). A number of garlic preparations are available on the market as natural health products for humans, including garlic powder, essential oils, extracts and capsules (Botas et al., 2019). A large body of literature has studied the effects of dietary supplementation with garlic products on the growth performance and product quality of monogastric animals (mainly poultry and pigs), with some studies observing preliminary beneficial effects (Ogbuewu et al., 2019; Yan et al., 2011).

Recently, garlic products such as garlic powder, oil, extracts (allicin) and by-products (Fig. 1), as alternatives to antibiotics, have been used to manipulate the rumen ecology to achieve better growth performance, reduce methane emissions, and improve the quality of ruminant products and the control of parasite infections (Curry and Whitaker, 2010; Ogbuewu et al., 2019). Studies have demonstrated that garlic products have a variety of biological benefits to ruminants (Yang et al., 2021; Zafarian and Manafi, 2013). However, there is limited systematic information on the effects of the use of different kinds of garlic products during ruminant production. Therefore, the aim of this review was to evaluate the beneficial effects of garlic products on the antioxidant status, immune response, rumen ecology (fermentation, microbiome, methane emissions), growth performance, and quality of ruminant products, in order to provide a theoretical basis for further development and utilization of garlic products in ruminant production.

2. Chemical composition and bioactive compounds of garlic products

The chemical composition and contents of bioactive compounds in garlic products vary depending on the genotype, cultivation practices, growing conditions, plant density, soil type, fertilizer application rate and processing method of those products (Chen et al., 2019; Kewan et al., 2021; Petropoulos et al., 2018). A summary of the characteristic chemical composition and contents of bioactive compounds in garlic products is provided in Table 1.

Garlic powder, skin and leaf are protein-rich ingredients for use as animal feed additives or roughage. Garlic powder, skin and leaf are high in crude protein content compared with other forage types, and the protein contents of these garlic products are close to that of alfalfa hay (approximately 15.5% on a dry matter [DM] basis) (El Shereef, 2019; Wang et al., 2021b). More importantly,

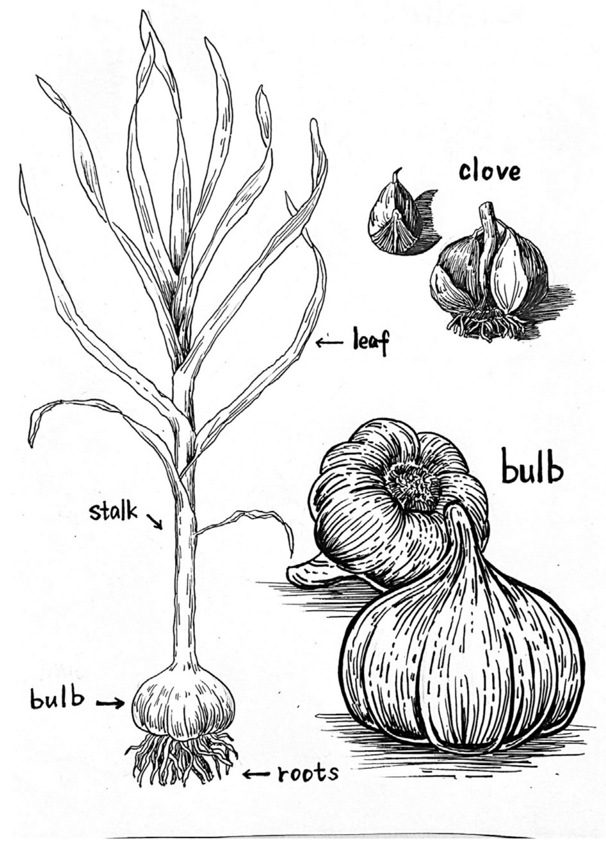

Fig. 1. The name of each part of the garlic plant. Garlic powder is from peeled garlic cloves after being ground; garlic oil is extracted from peeled garlic cloves with organic solvents; garlic straw refers to the sum of the stalk and leaf; garlic skin is obtained after husks of garlic cloves have been peeled.

the protein in garlic powder contains virtually all the essential amino acids required by animals; the most abundant amino acid is arginine, followed by aspartate and glutamate (Kodera et al., 2002). The protein contents of garlic powder, skin and leaf are reported to be approximately 22.90%, 13.50% and 12.80% on a DM basis, respectively (Kongmun et al., 2011; Panthee et al., 2017; Wang et al., 2013). Additionally, garlic powder and straw have high contents of total carbohydrates, approximately 74.25% and 80.90% on a DM basis, respectively (Drszczyk et al., 2019; Kewan et al., 2021). The dominant carbohydrate in garlic is polysaccharides, and the dominant polysaccharide is fructan, accounting for more than 75% of the DM content of garlic cloves (Yan et al., 2020). The neutral detergent fibre (NDF) and acid detergent fibre (ADF) contents of a feed are important parameters that are used to predict the nutrient digestibility and energy concentrations of the feed (Stergiadis et al., 2015; Yang et al., 2018). For ruminants, there is an inverse relationship between ADF and NDF contents and nutrient digestibility (Stergiadis et al., 2015). The NDF and ADF contents of garlic skin, leaf and straw are higher than those of powder; these garlic products can be used as a substitute for conventional roughage in the basic ruminant diet (Wang et al., 2021a,b). The NDF contents (DM basis) of garlic skin, leaf and straw are reported to be 31.81%, 59.80% and 51.18%, respectively, while those of ADF are 29.85%, 23.00% and 43.81%, respectively (Li and Fen, 2019; Panthee et al., 2017; Wang et al., 2021a,b). Garlic skin, leaf and straw have high ash contents due to the high contents of epidermal cells containing large amounts of silica (Redoy et al., 2020; Zhao, 2018).

Table 1
Chemical composition and bioactive compounds of garlic products.

Item	Garlic products			
	Powder	Skin	Leaf	Straw
Chemical composition, % DM				
DM	87.60–94.01	90.60–91.80	10.54–40.40	83.57–89.26
CP	16.30–22.90	13.10–13.65	11.83–24.80	5.73–9.56
TC	62.44–79.99	–	57.80–64.45	80.90–87.36
EE	1.38–2.99	4.20–4.50	4.45–4.50	1.02–4.12
Ash	3.93–6.97	5.60–7.95	15.53–18.82	10.74–17.78
NDF	7.40–18.09	31.81–58.40	59.80–84.32	34.61–51.18
ADF	5.58–14.07	29.85–44.40	23.00–65.23	27.25–43.81
Bioactive compounds				
TSC, % DM	0.421–0.658	–	–	–
TPC, mg GAE/g FW	0.43–0.64	12.88–16.74	–	6.36–12.40
TFC, mg CE/g FW	0.01–0.06	0.44–0.51	–	0.22–0.32
References[1]	El Shereef (2019)[2]; Kongmun et al., (2011)[2]; Zou and He (2020)[2]; Micová et al., (2018)[3]; Kahyaoğlu (2021)[3]	Wang et al., (2013)[2]; Bampidis et al., (2005)[2]; Wang et al., (2021a,b)[2]; Kahyaoğlu (2021)[3]	Panthee et al., (2017)[2]; Redoy et al., (2020)[2]; Meng (2015)[2]; Micová et al., (2018)[3]; Kahyaoğlu (2021)[3]	Drszczyk et al., (2019)[2]; Zhai et al., (2018)[2]; Lin et al., (2019)[2]; Kahyaoğlu (2021)[3]

DM = dry matter; CP = crude protein; TC = total carbohydrates; EE = ether extracts; NDF = neutral detergent fibre; ADF = acid detergent fibre; TSC = total sulphur content; TPC = total polyphenols content; TFC = total flavonoid content; GAE = gallic acid equivalent; CE = catechin equivalent; FW = fresh weight. –: no data provided by the references. TC = OM − (CP + EE).

[1] References with the number 2 mean that the chemical composition ranges of the garlic products are from these references, and those with the number 3 mean that the garlic bioactive compound ranges are from these references.

In terms of the bioactive compounds of garlic products, fresh or dried garlic bulbs are rich in organosulphur compounds. One study found that the total content of organosulphur compounds in garlic powder ranged from 0.56% to 0.80% on a DM basis (Micová et al., 2018). Alliin is the main active component of these organosulphur compounds, comprising more than 90% of the total organosulphur compounds in garlic powder; alliin is the precursor of allicin (Zhai et al., 2018). When raw garlic bulbs are crushed, cut or ground, the vacuolar enzyme alliinase is released into the cytoplasm to convert alliin into diallyl thiosulphinate (allicin) (Shin et al., 2017). Allicin is considered responsible for the antibacterial, antifungal, antiparasitic and anticancer activities of *Allium hirtifolium* (Omidifar et al., 2020; Roseblade et al., 2017). The anticancer activity of allicin is widely attributed to the allylthio group. However, this group is highly unstable and, as a consequence, allicin is readily decomposed into oil-soluble allyl polysulphides, such as diallyl disulphide, diallyl trisulphide and diallyl sulphide under relatively mild conditions (Roseblade et al., 2017; Xu et al., 2018) (Fig. 2). Studies have shown that allyl polysulphides display anticancer, lipid-lowering, anti-atherosclerotic and antioxidant effects in humans and animals (Lawson and Hunsaker, 2018). In addition, garlic also contains saponins, polysaccharides and flavonoids, which are also present in garlic skin and straw; these bioactive compounds confer diverse health benefits (Shang et al., 2019). Garlic skin and straw are characterized by their high contents of phenolic compounds. The total polyphenol (extracted by ethanol) contents of garlic powder, skin and straw reportedly range from 0.43 to 0.64, 12.88 to 16.74 and 6.36 to 12.40 mg/g fresh weight (FW), respectively (Kahyaoğlu, 2021; Micová et al., 2018); similar results were reported by Drszczyk et al., 2019. Garlic powder contains approximately 0.36% (DM basis) oil (Zou and He, 2020). The main constituents of garlic oil detected by gas chromatography-mass spectrometry chromatography are D-limonene, diallyl disulphide and diallyl trisulphide, whereas those of garlic water-soluble extract as detected by liquid chromatography-mass spectroscopy are N-acetylcysteine, cysteinyl-alanine and phenol-2-2-benzoxazolyl (Dewi et al., 2017).

3. Effects of garlic products on the growth performance of ruminants

Garlic products are alternatives to antibiotic and non-nutritive chemical feed additives. These products are added to the diet of ruminants to promote growth performance. The effects of garlic products on the feed intake, nutrient digestibility and growth performance of ruminants are summarised in Table 2. Garlic powder is the most common form of garlic utilised as a growth

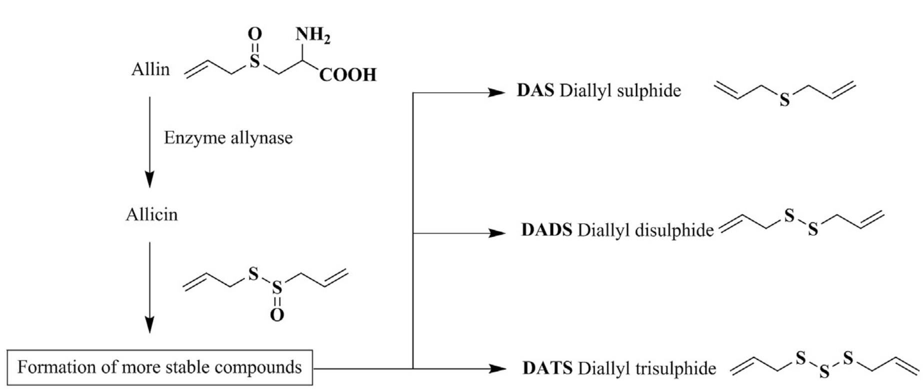

Fig. 2. Alliin transformation to more stable compounds. Adapted from Morales González et al. (2019).

Table 2
Effects of dietary supplementation of garlic products on ruminant growth performance.

Additive form	Dose, g/kg DM	Experimental period	Ruminants	Age	Parameters														Reference
					Growth performance			Feed intake			Nutrient digestibility								
					ADG	FCR	TWG	DMI	CPI	TDNI	DM	CP	CF	NFE	OM	EE	NDF	ADF	
Garlic powder	30 or 60	70 d	lambs	46 d	=	=	=	=	=	=	–	–	–	–	–	–	–	–	Bampidis et al. (2005)
	50	84 d	lambs	5 mo	↑	=	–	=	↑	–	↑	↑	–	–	–	=	=	=	Zhong et al. (2019)
	20	100 d	lambs	5–6 mo	↑	↓	–	–	–	–	↑	↑	↑	↑	↑	↑	–	–	El-Naggar and Ibrahim (2018)
	27	55 d	lambs	8 mo	↑	↓	–	=	–	↑	↑	↑	↑	↑	↑	=	–	–	Kewan et al. (2021)
	4	84 d	rams	yearling	↑	↓	↑	↑	↑	↑	–	–	–	–	–	–	–	–	Adegun et al. (2017)
	10	27 d	sheep	22 mo	–	–	–	=	=	=	↑	–	–	–	↑	–	↑	↑	Patra et al. (2011)
	5, 10 and 15	84 d	goats	6–7 mo	=	=	=	=	=	=	=	↓	=	–	–	=	=	=	Ikyume et al. (2017)
	7.5	150 d	calves	2–3 mo	↑	=	↑	=	–	–	–	–	–	–	–	–	–	–	Balamurugan et al. (2014)
	5	56 d	calves	100 d	↑	↓	–	↓	–	–	↓	=	–	–	–	–	=	=	Gholipour et al. (2016)
	2	6 mo	calves	12–14 mo	=	=	=	–	–	–	↑	=	↑	=	=	↑	=	=	Hassan and Abdel-raheem (2013)
	6.8 or 13.5	21 d	buffaloes	3 yr	–	–	–	=	=	=	=	↑	–	–	=	–	↓	↓ (13.5)	Kongmun et al. (2011)
Garlic skin	80	56 d	lambs	3.5 mo	↑	↓	–	=	=	=	–	–	–	–	–	–	–	–	Zhu et al. (2021)
Garlic husks	50 or 100	70 d	lambs	46 d	=	↓	–	=	=	=	–	–	–	–	–	–	–	–	Bampidis et al. (2005)
Garlic oil	1.2	63 d	lambs	2.5–3 mo	↓	=	↓	=	=	=	–	–	–	–	–	–	–	–	Canbolat et al. (2021)
Water extract of garlic	14	55 d	calves	5 d	↑	=	–	↑	↑	↑	–	–	–	–	–	–	–	–	Ghosh et al. (2011)
Garlic leaf	31	75 d	sheep	1 yr	↑	↓	↑	=	=	=	=	=	=	=	=	=	=	=	Redoy et al. (2020)

ADG = average daily gain; FCR = feed conversion ratio; TWG = total weight gain; DMI = dry matter intake; CPI = crude protein intake; TDNI = total digestible nutrient intake; DM = dry matter; CP = crude protein; CF = crude fibre; NFE = nitrogen-free extracts; OM = organic matter; EE = ether extracts; NDF = neutral detergent fibre; ADF = acid detergent fibre. ↑: increase; ↓: decrease; ↑ or ↓ with (x): the garlic products display effects at a specific dose of treatment; otherwise, all the doses (>0) described in the study display effects; =: no changes; –: no data provided by the references.

promoter in the ruminant feed industry. The dietary addition of garlic powder not only increases the digestibility of DM, crude fibre, crude protein (CP), nitrogen-free extracts and organic matter, but also improves the average daily gain (ADG) and feed conversion ratio (FCR) of lambs at the age of 5 to 8 mo. The recommended positive effective dose ranges from 20 to 50 g/kg on a DM basis with a 55 to 100 d experimental period (Kewan et al., 2021; El-Naggar and Ibrahim, 2018; Zhong et al., 2019). Studies have shown that the average daily gain of lambs infected by gastrointestinal nematodes is significantly increased after feeding garlic powder (50 g/kg of DM basis, 84 d experimental period); this is attributed to the antiparasitic property of garlic powder (Zhong et al., 2019). Moreover, dietary supplementation with garlic powder (5 to 7.5 g/kg DM) can increase the ADG and FCR of 2- to 3-mo-old calves in a 56- to 150-d experimental period (Gholipour et al., 2016; Balamurugan et al., 2014). The addition of garlic powder into the diet can enhance feed palatability, which, in turn, increases the animal's appetite and feed nutrient intake (El-Naggar and Ibrahim, 2018). Furthermore, garlic powder is rich in sulphur-containing compounds with antioxidant and antimicrobial activities; thus, the addition of garlic powder into the feed of ruminants can protect the feed ingredients from spoilage due to oxidation and microbial contamination during storage, which also improves the palatability of the feed (Omidifar et al., 2020; Samimi et al., 2019). Patra et al. (2011) reported that dietary addition of garlic powder (10 g/kg at DM basis for 27 d) can increase the digestibility of ADF and NDF, as the allicin in garlic powder can increase the population of cellulolytic bacteria (*Butyrivibrio fibrisolvens*, *Fibrobacter succinogenes*, and *Ruminococcus flavefaciens*), which, in turn, increases the digestibility of ADF and NDF (Ma et al., 2016). The mechanism underlying the increased digestibility of ADF and NDF may also be applicable to other nutrients. Nonetheless, dietary supplementation with garlic powder improves the growth performance (ADG and FCR) of lambs and calves primarily by increasing feed intake and nutrient digestibility. In contrast to the effects in lambs and calves mentioned above, for goats aged 6 to 7 mo, the provision of 5 to 15 g/kg (DM basis) of garlic powder for 84 d has no effect on growth performance and feed intake and can even decrease the digestibility of CP in a dose-dependent manner (Ikyume et al., 2017). The reasons for this phenomenon are not clear and remain to be further investigated.

In recent years, there has been great demand on the international market for garlic as a spice and traditional medicine, resulting in a large amount of garlic by-products, including garlic skin, leaf, straw and so on (Chen et al., 2020). Garlic by-products are abundant in protein, total carbohydrates and ash; therefore, they can be good sources of ingredients for ruminant feed. The effects of dietary supplementation with garlic by-products on the growth performance of ruminants are summarised in Table 2. Zhu et al. (2021) reported that the ADG and FCR of 3.5-mo-old lambs were improved after supplementation with garlic skin at 80 g/kg (DM basis) for 56 d. Polyphenols are the major bioactive compounds of garlic skin and can positively influence energy metabolism, resulting in higher energy utilization via a reduction in methane emissions in the rumen, which, in turn, promotes a higher ADG in Hu lambs (Zhu et al., 2021). The garlic leaf has a high CP content, and its NDF and ADF degradation rates in rumen fluid are higher than other roughages like peanut vine, bean stalk and sorghum shell. This suggests that garlic leaf is an easily digestible roughage that can be included in the diets of ruminants (Meng, 2015). Similarly, Redoy et al. (2020) claimed that the dietary addition of garlic leaf (31 g/kg, DM basis) for 75 d can improve the ADG, FCR and total weight gain of 1-yr-old sheep. However, it should be noted that the majority of these garlic by-products are typically abandoned or burned, resulting in environmental pollution (Han et al., 2012). Thus, there is a lack of literature on the effects of garlic by-products on nutrient intake and digestibility of ruminants. Therefore, more studies are needed in order to take full advantage of garlic by-products in ruminant feeding.

In addition to garlic by-products, garlic extract and oil are also used in ruminant feeding. Ghosh et al. (2011) reported that dietary supplementation with garlic water extract at 14 g/kg (DM basis) for 55 d could increase the intake of CP, DM and TDN in calves. Another study reported that 2.5- to 3-mo-old lambs fed garlic oil at a dose of 1.2 g/kg (DM basis) had lower ADG and total weight gain compared to those of the control group for a 63-d experimental period (Canbolat et al., 2021). Similar to garlic by-products, the effects of garlic extract and oil on nutrient intake and digestibility require further study in order to effectively implement these products in the practice of ruminant feeding. Essential oils, as secondary plant metabolites, are a source of various compounds, including terpenoids and polyphenols, and are reported to have strong antimicrobial properties, inhibiting the growth and survival of most microorganisms in the rumen. If the amount of garlic oil that is used in animal feeding is greater than the optimal amount, antimicrobial action against microorganisms will occur, which will influence the degradation of dietary nutrients. Thus, the addition of large amounts of garlic oil to the diet will decrease the utilization of nutrients, further reducing the growth performance of ruminants. Therefore, it is critical for researchers to determine the optimal supplementation dose of garlic oil for different types of ruminants.

The nutritional value of garlic products in terms of ruminant growth performance is an essential parameter considered by animal nutritionists. However, feed costs account for 50% to 70% of the total livestock production system profits (Verbeke et al., 2015). As a result, the economic costs associated with the addition of garlic products to ruminant diets should be carefully examined. Ghosh et al. (2011) reported that the feed cost (kilogram gain in body weight) in the group supplemented with garlic water extract decreased by 5.6% compared to that in the control group. In another study, due to the inhibition of mastitis during the first 14 d of lactation, the total feed costs decreased by approximately 35 Chinese yuan when cows were supplemented with garlic boluses during the dry period (Hartog, 2018). Systematic evaluation of the economic costs of the addition of garlic products to ruminant rearing systems is necessary as, to date, there is only limited published literature on this topic.

4. Effects of garlic products on the antioxidant activities and immune responses of ruminants

The endogenous antioxidant system is of vital importance for controlling reactive oxygen species (ROS) levels and maintaining the balance of the oxidation-reduction (redox) status of the body (Sugiharto et al., 2016). Endogenous antioxidant enzymes scavenge excessive ROS to prevent damage. Under basal conditions, endogenous antioxidant enzymes can keep pace with ROS formation (Dreyer, 2016). Superoxide dismutase (SOD), catalase (CAT), glutathione (GSH), total antioxidant capacity (T-AOC) and malondialdehyde are important enzymes in the endogenous antioxidant defence system (Holditch et al., 2019; Li et al., 2020; Lin et al., 2019; Wang et al., 2018).

The effects of garlic products on antioxidant activities are shown in Table 3. Garlic powder, skin and leaf have the potential to affect the activity of serum antioxidant enzymes to improve the antioxidant status of ruminants. Dietary garlic powder at a dose of 2% (DM basis) for 100 d was reported to improve the antioxidant status of 5- to 6-mo-old lambs by increasing T-AOC and reducing malondialdehyde (El-Naggar and Ibrahim, 2018). Yang et al. (2021) reported an increase in serum SOD after the addition of 150 g/kg (DM basis) of garlic skin into the diet of 4-mo-old lambs for 30 d. Redoy et al. (2020) reported that garlic leaf fed to 1-yr-old sheep at 31 g/kg (DM basis) for 75 d increased T-AOC, glutathione peroxidase, SOD and CAT in serum. Lee et al. (2020) demonstrated that the addition of a complex containing garlic extract (pinecone oil, garlic kernel, and brown seaweed midrib extracts at a ratio of 1:1:1, vol:vol:vol) to the basic diet of lactating Holstein-Friesian cows for 40 d tended to increase the antioxidant status of the cows, with increases in T-AOC and GSH concentrations compared to those of cows on 0 d. However, before a more precise conclusion can be made, the effects of various physiological states, such as the stage of lactation, on the antioxidant parameters of these cows should be verified and controlled for.

Nuclear factor erythroid 2-like 2 moves into the nucleus after separating from Kelch-like ECH-associated protein 1, and then interacts with antioxidant response elements to induce the expression of different antioxidant enzymes, such as GSH, SOD and CAT. These enzymes scavenge oxygen free radicals, promoting the fine balance between reductive and oxidative states (Samimi et al., 2019). *S*-allylcysteine, as a major organosulphur compound in garlic products, can promote the nuclear translocation of nuclear factor erythroid 2-like 2, allowing it to regulate the expression of various antioxidant enzymes through binding to antioxidant response elements, thus preventing oxidant damage to the body (Shi et al., 2015). However, the effects of various garlic products on antioxidant parameters differ significantly among various animals. Differences in the physiological status of the animal and the forms, concentrations and composition of bioactive compounds in garlic products are suggested to explain these inconsistent results.

Immunoglobulins such as immunoglobulin A (IgA), immunoglobulin G (IgG) and immunoglobulin M (IgM) are membrane-bound or secreted glycoproteins produced by B lymphocytes and are major secretory products of humoral immunity (Yang et al., 2020). IgM, IgA and IgG are the dominant immunoglobulins in serum and their levels serve as important indices of host humoral immune function (Shi et al., 2015). Garlic products can stimulate the immune response of ruminants by increasing the levels of immunoglobulins (Kewan et al., 2021; Redoy et al., 2020). Kewan et al. (2021) reported that dietary supplementation with 27 g/kg (DM basis) of garlic powder for 55 d increased IgA and IgG levels in the blood of 8-mo-old lambs. In another study, 1-yr-old sheep supplemented with 31 g/kg (DM basis) of garlic leaf for 75 d exhibited higher IgA and IgM levels in serum (Redoy et al., 2020). Ajoene is a bioactive compound in garlic products that may influence B-cell stimulation, producing immunoglobulin (Arreola et al., 2015). However, to date, the reported effects of garlic products on immunoglobulin levels are inconsistent. Therefore, more studies examining the effects of dietary supplementation with garlic products on ruminant immunoglobulin levels are necessary to further clarify the mechanisms underlying any potential effects of garlic supplementation on immunoglobulins.

5. Effects of garlic products on parasitic infections in ruminants

Parasitic infections impact ruminant production parameters including health, weight gain, feedlot performance, reproductive efficiency and carcass quality; this leads to economic losses in ruminant production systems (Andresen et al., 2018; Patten et al., 2011). In one study, a high infection rate of gastrointestinal parasites presented in small ruminants, with an overall occurrence of 98.4% (Win et al., 2020). Anthelmintic drugs are extensively used to cure parasite infections in animals (Mooney et al., 2019). However, with the frequent use of anthelmintics, the rate of anthelmintic resistance has been increasing (Babják et al., 2021). However, it has been reported that natural plant extracts possess anthelmintic properties due to their abundance of bioactive compounds, making them an important source for alternative anthelmintic drugs without causing resistance. The use of garlic powder and its extracts in ruminant feeding to control parasite infections has been introduced due to the antiparasitic properties of garlic, with research revealing remarkable results (Krstin et al., 2018; Strickland et al., 2009).

Table 3
Effects of garlic products on the antioxidant and immune responses of ruminants.

Form of garlic used	Additive dose, g/kg DM	Experimental period	Ruminants	Age	Significantly affected parameters	Reference
Garlic powder	27	55 d	lambs	8 mo	neutrophils↓, IgA↑, IgG↑	Kewan et al. (2021)
	2.5	84 d	rams	yearling	SOD↑, MDA↓, NO↓	Afele et al. (2020)
	20	100 d	lambs	5–6 mo	MDA↓, T-AOC↑	El-Naggar and Ibrahim (2018)
Garlic powder/oil	20 (powder, DM); 2 mL/d per ram (oil)	151 d	rams	3–4 yr	serum IgG (for oil)↑, colostrum IgG (both powder and oil)↑	El-Shereef (2019)
Garlic skin	50, 100, and 150	30 d	lambs	4 mo	$IgM\uparrow_{(150)}$, $SOD\uparrow_{(150)}$	Yang et al. (2021)
Garlic leaf	31	75 d	sheep	1 yr	IgA↑, IgM↑, T-AOC↑, GPx↑, SOD↑, CAT↑	Redoy et al. (2020)

DM = dry matter; IgA, IgG, IgM = immunoglobulin A, G and M, respectively; SOD = superoxide dismutase; MDA = malondialdehyde; NO = nitric oxide; T-AOC = total antioxidant capacity; GPx = glutathione peroxidase; CAT = catalase. ↑: increase; ↓: decrease; ↑ or ↓ with (x): the garlic products display effects at a specific dose of treatment; otherwise, all doses of the garlic products (>0) described in the experiment display effects.

A faecal egg count is the most common indicator of parasitic infection; it involves the measurement of the number of eggs per gram of faeces (Ngere et al., 2018). In one study, 90-d-old sheep were orally administered 1 teaspoon/sheep of natural garlic extract (Garlic Barrier, Glendale, CA, USA) and were found to have a significantly lower faecal egg count, heavier body weight and higher packed cell volume compared to sheep in the control group for 153 d (Curry and Whitaker, 2010). Sheep orally administered a 10% water solution of garlic (25 or 50 mL) for 60 d exhibited similar results to those that were treated with natural garlic extract at 18 to 22 mo of age (Hasan et al., 2015). The inclusion of garlic granules (0.54% DM) in the diet for 2 wk was found to produce a 64.4% reduction in the faecal worm egg counts in 4-mo-old sheep infected with *Haemonchus contortus*. There was also an apparent long-lasting effect of garlic granules as there was no difference in the worm egg counts during or after therapy, which suggests that garlic may affect the fecundity as well as the mortality of the parasite (Strickland et al., 2009). In another study, aqueous and alcoholic extracts of garlic produced 100% killing effects during the larva stage, with all cultured worms being completely immotile on the 4th and 5th d post-exposure (Ahmed and AL-jubori, 2020). The above-described antiparasitic properties of garlic extracts are important factors underlying the growth promotion effects of garlic extracts in sheep.

6. Effects of garlic products on ruminal microbial ecosystems

6.1. Rumen microbiota

Garlic and its products are rich sources of secondary plant metabolites such as allicin and phenolics, which are responsible for the antimicrobial activity of garlic (Kamra et al., 2012). Several studies have demonstrated that dietary supplementation of a ruminant animal's diet with garlic and its products can serve as a rumen modifier. In one study, 8-mo-old lambs were fed garlic powder at 27 g/kg (DM) for 55 d and a decrease in the total number of protozoa in the rumen was observed (Kewan et al., 2021). Similarly, another study reported that dietary supplementation with allicin, which is a secondary plant metabolite in garlic bulbs, decreased the number of protozoa and increased the number of total bacteria and cellulolytic bacteria (*F. succinogenes, R. flavefaciens, and B. fibrisolvens*) in 12-mo-old ewes for 42 d (Ma et al., 2016); this latter effect was due to the reduction in the number of protozoa, which are able to engulf bacteria in the rumen as their main protein (Belanche et al., 2014). Moreover, an increase in cellulolytic bacteria can improve the utilisation of dietary fibre and supply more carbohydrates to microbes (Ma et al., 2016). Novel omics methods like metagenomics, metabolomics, transcriptomics and proteomics can provide a better understanding of the impact of dietary ingredients on the rumen ecosystem. Zhu et al. (2021) performed 16S rDNA sequencing and metabolomics analysis and reported that the relative abundances of the genera *Bulleidia* and *Prevotella* were increased by dietary supplementation with garlic skin at 8% DM in total mixed ration for 56 d. Saccharides and starch can be utilised by *Bulleidia* as a source of energy, and *Prevotella*, a dominant rumen bacterium, are able to degrade fibre in the rumen. Therefore, garlic skin can increase the total volatile fatty acid content through the degradation of fibre and carbohydrates (Zhu et al., 2021).

To the best of our knowledge, the effects of garlic products, particularly by-products such as garlic leaf, skin and straw, on the diversity of the rumen microbiome have not yet been extensively studied. However, it is well known that rumen microbial communities are closely related to ruminant growth performance and nutrient digestibility (Du et al., 2019). Studies have demonstrated that garlic products can benefit ruminant growth performance and nutrient digestibility, indirectly suggesting that garlic products may influence the diversity and composition of the rumen microbiome. Therefore, systematic studies investigating the effects of garlic products on rumen microbial communities are essential to shed light on the mechanisms underlying the effects of garlic products on growth performance and nutrient digestibility.

6.2. Rumen fermentation

The complex rumen microbiota is responsible for digesting almost all types of roughage through fermentation, providing 70% to 80% of the energy requirements of ruminants via the production and absorption of volatile fatty acids from the fermentation process (Li et al., 2016; Makanya et al., 2020). Therefore, rumen fermentation parameters can reflect the efficiency of feed nutrient use in the rumen, and changes in the relative abundance of the rumen microbiome by dietary supplementation with garlic products can induce changes in the rumen fermentation pattern. Effects of garlic products on rumen fermentation parameters are shown in Table 4. Dietary addition of garlic powder (5 to 15 g/kg on a DM basis, for 84 d) decreases the rumen pH, while the pH is increased by dietary supplementation with garlic oil (0.4 to 1.2 g/kg on a DM basis, for 63 d). However, both powder and oil maintain the rumen pH within the normal range (Ikyume et al., 2017; Canbolat et al., 2021), which is reported to be between 6.3 and 6.8; this is ideal for supporting the normal activity of cellulolytic bacteria (Viennasay and Wanapat, 2020). The major end-product of dietary protein and non-protein nitrogen (urea and amino acids) metabolism is rumen NH_3–N, which provides ruminal bacteria with nitrogen for microbial protein synthesis (Li et al., 2016). Dietary supplementation of 5-mo-old lambs with garlic powder at 50 g/kg (DM basis) for 84 d, dietary supplementation of pregnant ewes with garlic oil at 2 mL/d per ewe for 122 d, and dietary supplementation of 3.5-mo-old lambs with garlic skin at 80 g/kg (DM basis) for 56 d were all found to result in lower rumen NH_3–N, indicating increases in rumen microbial

Table 4
Effects of garlic products on rumen fermentation parameters.

Additive form	Dose, g/kg DM	Experimental period	Ruminants	Age	Vivo/Vitro	Rumen fermentation parameters									Reference
						pH	NH_3–N	Acetate	Propionate	A:P ratio	Butyrate	Lactic acid	CH_4	TVFA	
Garlic powder	50	84 d	lambs	5 mo	vivo	↓	↓	↑	↑	↓	=	–	–	↑	Zhong et al. (2019)
	5, 10 and 15	84 d	bucks	6–7 mo	vivo	↓	↓	=	=	=	=	–	–	=	Ikyume et al. (2017)
	2	6 mo	calves	12–14 mo	vivo	=	↓	–	–	–	–	–	–	=	Hassan and Abdel-raheem (2013)
	20	100 d	lambs	5–6 mo	vivo	=	↑	–	–	–	–	–	–	=	El-Naggar and Ibrahim (2018)
	6.8 or 13.5	21 d	buffaloes	3 yr	vivo	=	=	↓	↑	↓	=	–	↓	↓	Kongmun et al. (2011)
	20	120 d	Murrah buffaloes	2nd to 3rd lactation	vivo	–	–	–	–	–	–	–	↓	–	Zafarian and Manafi (2013)
Garlic skin	8% garlic skin replacing equal percentage of the total mixed ratio (DM)	56 d	lambs	3.5 mo	vivo	=	↓	=	=	=	=	–	–	↑	Zhu et al. (2021)
Garlic oil	2 mL/d per sheep	122 d	sheep	the pregnant	vivo	=	↓	–	–	–	–	–	–	=	Mahmoud and Salah (2017)
Garlic oil	0.4, 0.8 and 1.2	63 d	lambs	2.5–3 mo	vivo	↑	↓	↓	↓	↓	↓	↓	–	↓	Canbolat et al. (2021)
Garlic oil	1.0, 2.5, and 5.0 μL per 30 mL of buffered rumen fluid	after 24 h of incubation	Murrah buffalo steers	2.5 yr	vitro	–	↓	↓(2.5, 5.0)	↑(5.0)	↓(1.0, 2.5)	↑(1.0)	–	↓	–	Dey et al. (2021)
Garlic oil	3, 30, 300 and 3000 mg/L of rumen fluid	8 d	–	–	vitro	↑(300, 3000)	↑(300)	↓(30, 300, 3000)	↑(30, 300, 3000)	–	↑(30, 300, 3000)	–	↓	↓(300, 3000)	Busquet et al. (2005)

DM = dry matter; A:P = acetate to propionate ratio; TVFA = total volatile fatty acids. ↑: increase; ↓: decrease; ↑ or ↓ with (*x*): the garlic products display effects at a specific dose of treatment; otherwise, all doses of garlic products (>0) described in the experiment display effects; –: no data provided by the references; =: no changes.

protein synthesis (Mahmoud and Salah, 2017; Zhong et al., 2019; Zhu et al., 2021).

With respect to garlic extracts, the addition of methanol and ethanol extracts of garlic (both at 0.5 mL/30 mL of rumen fluid) into in vitro incubation medium from buffalo rumen liquor was found to decrease the acetate to propionate ratio, resulting in a shift in volatile fatty acid production towards more propionate (Patra et al., 2010). In terms of garlic powder, feeding of garlic powder at 7.8 g/kg (DM basis) to Holstein Friesian crossbred steers for 21 d led to increased propionate production, a reduction in the acetate to propionate ratio, and obvious antibacterial and protozoal activities due to a reduction in the bacterial and protozoal population in the supplemented group (Wanapat et al., 2008, 2013). Another study reported that dietary supplementation with garlic powder at 50 g/kg (DM basis) for 84 d significantly increased the production of propionate and total volatile fatty acids and decreased the acetate to propionate ratio in 5-mo-old lambs (Zhong et al., 2019). With respect to garlic oil, studies have reported that the addition of garlic oil (300 mg/L of in vitro rumen incubation fluid) for 8 d can decrease the proportion of acetate and increase the proportions of propionate and butyrate in both continuous and batch culture systems (Busquet et al., 2005, 2006). In relation to garlic by-products, supplementation of 3.5-mo-old lambs with garlic skin at 80 g/kg (DM basis) for 56 d may improve carbohydrate fermentation in the rumen, producing a greater amount of total volatile fatty acids which can be absorbed via the rumen wall as the main energy substance for ruminants; however, no effects on the proportions of other volatile fatty acids have been observed (Zhu et al., 2021). In summary, dietary supplementation with garlic products can increase the concentrations of propionate and butyrate and reduce the concentration of acetate in the rumen. Therefore, garlic products have the potential to improve the energy supply of ruminants, since propionate is the primary substrate for hepatic gluconeogenesis, which supplies 24% to 61% of the total energy requirements of ruminants (Vyas et al., 2018). In addition, higher propionate production in the rumen may reflect the inhibitory effects of garlic products on methane emissions, as the propionate pathway is a hydrogen consumer. Thus, a reduction in the hydrogen produced in the rumen may reduce the synthesis of methane and improve the efficiency of feed nutrient utilization in ruminants.

6.3. Methane emissions

Methane emissions during ruminal fermentation represent a 2% to 12% loss of ingested dietary energy, which indicates a decrease in feed utilization (Johnson and Johnson, 1995). Approximately 80% of emissions from the agricultural sector are methane emissions from ruminants. It should be emphasized that the global warming potential of methane is 25 times that of CO_2, and the contribution rate to the greenhouse effect is approximately 22%, resulting in rapid intensification of the greenhouse effect (Xue et al., 2021). Therefore, many studies have investigated the use of plants or their products to manipulate rumen microbial diversity and fermentation so as to decrease the methane emissions of ruminants (Adejoro et al., 2019).

Garlic powder, oil and allicin are able to reduce the methane emissions of ruminants (Dey et al., 2021; Ma et al., 2016; Zafarian and Manafi, 2013). Zafarian and Manafi (2013) demonstrated that the addition of 20 g/kg of garlic powder (DM basis) into the diet for 120 d can produce a 31% reduction in methane emissions from lactating Murrah buffaloes. In an in vitro study, garlic oil (1.0, 2.5 and 5.0 μL/30 mL of rumen fluid from buffalo steers) decreased methane emissions after 24 h of rumen fluid incubation (Dey et al., 2021). Moreover, garlic powder and oil have been shown to decrease methane emissions in a dose-dependent manner (Nanon et al., 2015; Sahli et al., 2018). Methanogenic archaea are the sole microbiome producing methane in the rumen (Belanche et al., 2016). Various organosulphur compounds, like allicin, that are present in garlic or its products have the potential to inhibit archaeal community membrane lipid synthesis, decreasing the population of methanogenic archaea and resulting in a reduction in methane emissions (Mbiriri et al., 2015). On the other hand, methanogens are clearly related to protozoa, either ecto- or endo-symbiotically, and up to 25% of methane emissions from rumen fluid in sheep are due to endo- and ecto-symbiotic methanogens associated with protozoa (Ma et al., 2016; Patra and Yu., 2015). Organosulphur compounds such as allicin reduce the populations of protozoa leading to a reduction in hydrogen production, which results in decreased rumen methane emissions through lower hydrogen availability for methanogens. Additionally, supplementation with garlic powder and oil can decrease the proportion of acetate but increase the proportion of propionate (Dey et al., 2021; Zafarian and Manafi, 2013). Propionate is negatively correlated with methane production, due to the competition for hydrogen, while acetate is positively related to methane emissions; therefore, garlic products mainly decrease methane emissions by altering the proportion of important short-chain volatile fatty acids in the rumen, particularly propionate and acetate (Suybeng et al., 2020).

To date, the relationship between the relative abundance of methanogenic archaea and methane emissions remains unclear (Ghanbari Maman et al., 2020; Wallace et al., 2015), as the rumen is a complex micro-ecosystem with a huge and varied microbial community (Wang et al., 2020). In addition, few studies have investigated the relationship between the proportion of methanogenic archaea and reduced methane emissions from sheep fed garlic products. Nonetheless, improvements in high-throughput technologies have fuelled the proliferation of omics applications in various research fields (Levi et al., 2021), and studies of the rumen microbiome are no exception (Xue et al., 2020). Thus, more studies using omics applications are needed to reveal the relationship between the relative abundance of methanogenic archaea and methane emissions. The results of such studies will assist in identifying the complex mechanism underlying the reduction in methane emissions by garlic product supplementation.

7. Effects of garlic products on product quality of ruminants

7.1. Meat quality of ruminants

Meat quality, including sensory traits, physicochemical properties and nutritional value, plays an essential role in consumer acceptance, food choices and market value (Freitas et al., 2019; Smaldone et al., 2019). Various factors affect meat quality, including breed, age, sex, nutrition and management (Ding et al., 2021). Among these factors, nutritional regulation is an effective, convenient and important approach to improving meat quality. Recently, the use of plants and their extracts as feed additives has been shown to improve meat quality by improving the flavour of the meat from ruminants, increasing the tenderness of this meat, and positively affecting the fatty acid composition of the meat due to the bioactive benefits of the various secondary plant metabolites (Cimmino et al., 2018; Garcia-Galicia et al., 2020). Products of garlic, onion and *Allium mongolicum* Regel belong to the *Allium genus* and are widely used in animal feeding to improve the quality of animal products; the beneficial biological efficacy of these products on meat quality has been demonstrated (Aditya et al., 2017; Ding et al., 2021; Mancini et al., 2020).

Effects of garlic products on ruminant meat quality are shown in Table 5. One study evaluated the effects of dietary supplementation of different doses (0, 18 or 38 g/kg DM) of garlic powder for 10 wk

Table 5
Effects of garlic products on ruminant product qualities.

Form of garlic used	Additive dose, g/kg DM	Experimental period	Product	Ruminants	Age	Significantly affected parameters	Reference
Garlic (fresh)	18 and 36	70 d	meat	wethers	4 mo	best taste↑$_{(36)}$	Strickland et al., (2011)
Garlic leaf	31	75 d	meat	sheep	1 yr	saturated fatty acids↓; unsaturated fatty acids↑	Redoy et al., (2020)
Garlic oil	0.2	91 d	meat	lambs	weaning	off-flavour intensity↓	Chaves et al., (2008)
Garlic stalk silage	0.22% (the fattening period) and 0.33% (the finishing period) BW/d	22 mo	beef	steers	5 mo	tenderness, linoleic and linolenic acids and essential amino acids↑	Chu et al., (2003)
Garlic powder/oil	20 (powder, DM); 2 mL/d per ram (oil)	151 d	milk	rams	3–4 yr	CLA and n-3 fatty acids↑	EI-Shereef (2019)
Garlic oil	5 g/d per cow	21 d	milk	dairy cows	midlactation	cis-9, trans-11 CLA↑	Yang and He (2016)
Garlic powder	5 g/d per cow	21 d	milk	cows	–	somatic cell counts↓; colony forming units↓	Bochenek and Kuczyńska (2019)

DM = dry matter; CLA = conjugated linoleic acids. ↑ = increase; ↓ = decrease; ↑ or ↓ with (x) = the garlic products display effects at a specific dose of treatment; otherwise, all doses of garlic products (>0) described in the experiment display effects; – = no data provided by the references.

on the flavour, panellist's comments, and acceptability of cooked lamb meat. The results indicated that the addition of 36 g/kg of garlic powder was the only dose that improved consumer's acceptance of the cooked meat; the other dietary doses of garlic powder had no significant effects on the flavour of the lamb meat (Strickland et al., 2011). Few studies have accurately evaluated the effects of garlic powder dietary supplementation on the flavour of ruminant meat. In contrast, *A. mongolicum* Regel (AMR), another plant belonging to the *Allium* genus, has been shown to decrease sheep meat flavour and odour by reducing the concentrations of 4-methyloctanoic acid, 4-methylnonanoic acid and 4-ethyloctanoic acid in adipose tissue (Liu et al., 2018). Therefore, it is necessary to further explore whether dietary supplementation with garlic powder can improve the flavour of ruminant meat. Chaves et al. (2008) reported that dietary supplementation with garlic oil (0.2 g/kg on a DM basis for 13 wk) had minor effects on the sensory quality (only for decreasing off-flavour intensity) of lamb meat. However, secondary compounds in plants exhibit strong dose-dependent effects on meat quality (Vasta and Luciano, 2011). Thus, various gradients of garlic oil should be evaluated to more accurately verify their influences on sheep meat flavour and odour. Tenderness is one of the most important determinants of meat quality, affecting consumer's assessments of meat quality (Xiang et al., 2018). Shear force is used as a common indicator of meat tenderness (Alarcon-Rojo et al., 2015); lower shear force values are associated with more tender meat (Tricarico et al., 2016). Garlic stalk silage fed to Hanwoo steers at ratios of 0.22% and 0.33% BW in the fattening and finishing periods for 22 mo, respectively, was found to significantly decrease the shear force value of beef, indicating that garlic stalk silage has the potential to improve the tenderness of beef (Chu et al., 2003). Lipid and protein oxidative reactions can significantly degrade meat quality and reduce the shelf-life of meat products. Due to the presence of antioxidant active components, garlic products may have the potential to boost the oxidative stability of meat, and thus, lengthen the self-life of meat while maintaining its sensory qualities (Vasta and Luciano, 2011). In addition, interestingly, the water holding capacity of mutton from sheep fed AMR is significantly higher than that of control sheep during the product's shelf life (Liu and Ao, 2021). However, to date, there are few published studies evaluating the effects of dietary supplementation with garlic products especially for garlic by-products on ruminant meat antioxidant status and physicochemical properties during the storage period. Thus, much effort is needed to fill this gap in order to provide a basis for the full use of garlic products.

Polyunsaturated fatty acids (PUFA) and essential amino acids in animal products have significant functions in maintaining human health (Sewczyk et al., 2018; Wang et al., 2021a,b). The optimization of fatty acid and amino acid compositions in animal products by dietary supplementation with plants and their extracts is a challenge but an important target for animal nutritionists. Garlic stalk silage (at ratios of 0.22% and 0.33% BW in the fattening and finishing periods, respectively) fed to sheep for 22 mo has the potential to improve the nutritional value of mutton by increasing the concentrations of linoleic and linolenic acids and essential amino acids. Linoleic acid provides protection against various conditions, such as cardiovascular and autoimmune diseases, and essential amino acids are fundamental nutrients for human health (Chu et al., 2003; Li et al., 2021; Ren et al., 2021). The chemical composition of garlic stalk is similar to that of garlic; both have higher oleic acid resulting in the accumulation of linoleic acid in mutton, as oleic acid is the precursor of linoleic acid. In addition, the effects of organosulphur compounds in garlic stalk on rumen hydrogenation of dietary unsaturated fatty acids should also be considered.

7.2. Milk quality of ruminants

Effects of garlic products on ruminant milk quality are shown in Table 5. The dietary addition of raw garlic at a range of 30 to 70 g/kg (DM) for 14 d can efficiently reduce the concentration of fat in milk from 4-yr-old goats (Zakeri Zahra and Ehsan Anassori, 2014). The possible reason for this decrease in milk fat is that acetate from the rumen, which is used in the synthesis of milk fat, is decreased by dietary supplementation of garlic products (Kholif et al., 2017; Kongmun et al., 2011). Sheep fed a diet supplemented with garlic powder at a dose of 20 g/kg (DM) for 151 d produce milk with higher concentrations of conjugated linoleic acids (CLA) and n-3 fatty acids, which is healthy for consumers (EI-Shereef, 2019). Similar to garlic powder, the addition of garlic oil (2 mL/d per goat) to the basic diet of lactating goats for 90 d can also efficiently reduce the milk fat of the produced milk (Kholif et al., 2017). Furthermore, Yang and He (2016) reported that supplementation of dairy cows with garlic oil at 5 g/d per cow for 21 d can increase the concentration of cis-9, trans-11 CLA in the produced milk, which is a fatty acid isomer of linoleic acid produced by rumen bacteria (Renner et al., 2013). The cis-9, trans-11 CLA has been shown to possess anti-inflammatory, antidiabetic and anticancer properties (Thanh et al., 2021). Thus, garlic oil fed to dairy cows can improve the nutritional properties of milk by increasing the concentration of cis-9, trans-11 CLA. The mechanism underlying the effects of dietary supplementation with garlic powder and oil on the fatty acids in milk requires further investigation. Metabolism of the PUFA in essential oils is influenced by rumen biohydrogenation, which, in turn, affects the fatty acid composition of ruminant products (Yang and He, 2016). Zhu et al. (2013) reported that the results of rumen biohydrogenation of fatty acids are consistent with that of milk fatty acid profiles. The higher passage rate of digesta in the rumen of smaller ruminants compared to that of large ones limits the ability of the rumen microbiome to complete the biohydrogenation process of PUFA contained in essential oils (garlic oil) in the rumen; this may result in more deposition of PUFA in the products of smaller ruminants (Yang and He, 2016). Other studies have reported that dietary supplementation of lactating cows with a combined extract from garlic, brown seaweed (*Undaria pinnatifida*) and pinecone (*Pinus koraiensis*) (0.016% DM) for 40 d can effectively improve the milk yield, while the shear force and shear work of cheese were reduced by the dietary addition of diallyl sulphide and garlic at the ratio of 2 g/d per cow for 21 d (Lee et al., 2020; Rossi et al., 2018). Further studies are required to reveal the accurate mechanism underlying the effects of garlic products on cheese quality (Rossi et al., 2018). Use of garlic water extract as a pre-milking dairy cow teat sanitizer can significantly lower bacterial counts in teats and milk, producing high-quality milk for consumers (Mureza et al., 2021). Furthermore, cow and camel yogurt made with 85 mL of full cream milk, 5 g of starting culture and 10 mL of garlic water extract was found to have stronger antioxidant activities than those made without garlic water extract (Shori and Baba, 2014). Processes such as the sanitization of pre-milking dairy cow teats with garlic water extract and the mixing of garlic water extract with milk to improve the antioxidant status of yoghurt are complex and are considered a waste of time and money. However, if dietary supplementation with garlic extract also demonstrates an antibacterial function in dairy cow teats and improves the antioxidant activities of ruminant milk products, this would avoid the significant manpower and material resources while increasing the economic gain. Future trials should, therefore, focus on these aspects in order to improve the efficiency and economy of the use of garlic products in ruminant production.

In summary, more studies are needed to confirm the effects of garlic powder or oil on the concentrations of beneficial fatty acids in milk and to determine the most suitable supplementation dose to improve milk quality. Various garlic by-products, including garlic leaves, skin and straw, are increasingly available as the worldwide production of garlic continues to increase to meet consumer demand (Charron et al., 2015). Furthermore, the secondary plant metabolites in garlic by-products are similar to those in garlic (Ren et al., 2021). Thus, it is necessary to explore the influences of various garlic by-products on the concentrations of fatty acids in order to make full use of garlic by-products to improve the quality of products derived from ruminant animals.

8. Areas of future research

Further studies are needed to define the optimum dietary supplementation dosage of garlic products to achieve the best effects on growth performance, methane emissions, parasitic infections and product quality. Further, the mechanisms underlying the positive effects of garlic products should be investigated through biochemistry and omics technologies. Studies of the effects of dietary supplementation of garlic products and their bioactive compounds on the preservation of ruminant product (especially meat and milk) quality during storage should also be conducted. In addition, in future, studies should clearly state whether there is combination or synergistic effects of the bioactive compounds in garlic products, in order to take better advantage of the use of garlic products or their bioactive compounds in animal husbandry.

9. Conclusion

Dietary supplementation with garlic products is able to influence the diversity of the rumen microbiota, leading to changes in the rumen fermentation pattern, inhibition of methane emissions, more effective utilization of nutrients, improved growth performance of ruminants, and finally, improved quality of ruminant products.

Author contributions

He Ding wrote the manuscript. **Xiaoqing Zhang** and **Changjin Ao** conceived the study. All authors have read and approved the manuscript.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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