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Alfalfa quality improvement and loss reduction technology advances

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Forage is an indispensable feed for livestock, and the world is currently facing an imbalance in the “human-grass-livestock” relationship, with a sharp disparity between grass and livestock fundamentally due to insufficient forage resources. It is urgent to promote the development of a high-quality forage industry. According to Mordor Intelligence, the global alfalfa market is expected to reach $25.6 billion in 2024, with a compound annual growth rate of 6.03%, showing strong growth momentum. Optimizing alfalfa, a high-quality forage material with huge volume in the world, modulation and processing technology, exploring the key technologies of improving quality and reducing loss, reducing cost and increasing efficiency, and increasing its application path in livestock feeding, are the key issues to be solved urgently. This article reviews relevant literature published domestically and internationally. The key technologies for alfalfa storage and processing were summarized, and the nutritional value of high-quality forage and the key factors affecting its effectiveness explored, in order to provide references for production technicians and scientific researchers.

KEYWORDS

forage, alfalfa, bioactive components, conditioning, processing

Introduction

In recent years, there has been a significant upswing in the demand for beef, lamb, and dairy products among Chinese residents, yet domestic production has struggled to keep pace (Pi et al., 2004; Wang and Xin, 2021). This discrepancy can largely be attributed to an insufficient supply of forage, particularly high-quality forage (Jiang et al., 2023). The primary challenge to food security currently stems from feed grains. A strategic approach to mitigate this issue is to augment the forage supply and curtail the use of concentrate feed in cattle and sheep farming. The nutritional profile and composition of feed grains are instrumental in the normal growth and development of livestock (Han et al., 2020). Consequently, while reducing concentrate feed, it is imperative to ensure that pelleted feed processing technology positively influences cattle growth performance and rumen function. However, global feed grain supplies are under duress, especially in developing countries. Therefore, expanding forage supply, optimizing feed structure, and enhancing feed utilization efficiency are pivotal directions for the evolution of global animal husbandry. To realize these objectives, the global livestock industry must bolster scientific and technological innovation, elevate the efficiency and quality of forage production, foster international cooperation to facilitate trade and exchange of forage and feed, and strengthen policy guidance to encourage and support the forage industry. These measures are anticipated to drive sustainable development in the global livestock industry and cater to the burgeoning demand for meat and milk.

The global forage cultivation area spans 450 million hectares, accounting for 24% of the land area, making it one of the largest natural ecosystems worldwide (Lin et al., 2023). The scientific and moderate utilization of forage resources and a stable supply of high-quality forage are crucial to enhancing the quality and efficiency of animal husbandry and boosting farmers' incomes (Chen et al., 2013). Alfalfa (*Medicago sativa* L.), a superior forage, boasts high yield, nutritional value, palatability, total energy, digestion energy, robust nitrogen fixation, and stress resistance. It can be directly fed, grazed, or processed into silage, green hay, granules, and other products such as grass blocks, meal, and cakes. Widely used in dairy cattle feeding, alfalfa, when fed appropriately, significantly improves dairy cow production performance and is extensively employed in ruminant livestock production. Its roots, stems, and leaves are rich in bioactive substances, endowing it with antiviral and antioxidant properties that enhance animal immune function (Zeng et al., 2020).

The optimal harvest period for alfalfa ranges from the bud stage to the first flowering stage. The combination of hay and silage making is the most prevalent storage method currently, addressing time and space limitations in large-scale pastures. Incorporating varying proportions of alfalfa silage or equivalent replacement base diets can substantially enhance the intestinal flora activity, production performance, and product quality of livestock and poultry. Animal partial mixed ration (PMR) combined with fresh alfalfa can improve feed intake. Fernandez-Turren et al. (2023) accurately evaluated the nutritional efficiency of feeding lambs with PMR containing grain fiber by-products as an energy source supplemented with fresh alfalfa. A suite of research advancements underscores alfalfa's significant role in enhancing livestock nutrition, improving animal product quality, and ensuring animal intestinal health. Studies have demonstrated that PMR combined with fresh alfalfa positively affects the nutritional intake of lambs (Sun et al., 2023), influences the antioxidant activity of lamb meat by improving intestinal flora (Zhong et al., 2023), and under different feeding conditions, results in superior chemical digestion, antioxidant capacity, and stomach muscle layer thickness compared to ordinary feeding. Tarnonsky et al. (2023) showed that replacing corn silage with alfalfa haylage in the diet of growing beef cattle can increase feed intake and reduce weight gain rate, although a slower weight gain rate can be compensated for during the finishing period, achieving similar harvest weight and back fat thickness at similar feed ages. Wang et al. (2023) demonstrated that *Leymus chinensis* hay and alfalfa hay can lead to different meat metabolic product depositions by altering rumen bacterial communities.

This article, based on the properties of different high-quality alfalfas, addresses research gaps in the actual production of forage alfalfa, aligns with industry development trends, and proposes key research directions for alfalfa processing and modulation technology. It elucidates the nutritional value and key influencing factors of different processing technologies of alfalfa, thereby contributing to global ecological and food security and laying a comprehensive foundation for food security.

Overview of alfalfa scale and yield

As the largest consumer and exporter of alfalfa, the United States has strong advantages in basic research, technology development, variety cultivation, and commercial production of alfalfa, driving the development of the global alfalfa market. The growth rates of the global alfalfa market in various regions are shown in Figure 1. The planting area is approximately 8 million hm^2 in size (Yang et al., 2016) and alfalfa production exceeded 74 million tons, ranking first in the world (Ge and Wu, 2000). European and American multinational enterprises control the key links of the chain of the global alfalfa industry, which is the main export market of alfalfa products, and Asia has the largest consumption gap of alfalfa products (Xie et al., 2021). By 2020, China had expanded its alfalfa planting area to 366,850 hectares (Lu, 2021). However, by the close of 2021, the production volume had increased to 1,596,100 tons. The United States remains the predominant importer of alfalfa (Gao et al., 2022). Owing to the exorbitant costs associated with importing alfalfa hay, the paucity of high-quality hay resources domestically, the protracted germplasm breeding process, and a substantial reliance on foreign supplies, alfalfa silage has been increasingly adopted as a substitute for hay in most pastures. Nevertheless, the interchangeability of these two feed sources necessitates a comprehensive understanding of the nutrient composition alterations in alfalfa subjected to various modulation techniques.

In the context of soybean meal reduction initiatives aimed at promoting food conservation and curbing consumption, the Chinese amino acid industry stands at the forefront globally, possessing the capability to produce all essential amino acids required by animals. Both production and export volumes are among the world's highest, with most product prices having declined to levels acceptable to feed breeding enterprises. This development provides a robust foundation for the expanded promotion and application of low-protein diet technologies. Globally, efforts should be intensified to promote high-quality low-protein diet formulation technologies for pigs and chickens, expediting research into the feasibility of applying these diets to other livestock and poultry species. Concurrently, vigorous development of the forage industry, particularly enhancing the supply of high-quality forages such as alfalfa, is imperative to reduce feed grain consumption in cattle and sheep farming. Academician Qiao Shiyan, a professor at

China Agricultural University, advocates for the vigorous promotion of formulation technologies for high-quality low-protein diets for pigs and chickens, alongside accelerated research into the feasibility of extending these diets to other poultry breeds. The development of the forage industry, with a focus on increasing the supply of high-quality forages such as alfalfa and ryegrass, is crucial to reducing feed grain consumption in cattle and sheep farming. The inclusion of high-quality forages like alfalfa in animal diets has been shown to optimize production performance and enhance meat quality. Moreover, these forages offer advantages such as robust stress resistance, high pest and disease resistance, and enhanced resilience to environmental stresses. Integrating high-quality forages into feed not only contributes to reducing the overall cost of breeding but also fortifies the animals' resistance capabilities (Ma, 2019).

Nutritional value and bioactive substances of high-quality forage

Nutritional value of high-quality forage

Table 1 shows the main nutrient content of alfalfa.

Alfalfa products have different nutritional values and functional characteristics in animal feeding. Among them, alfalfa meal shows great application potential in improving animal digestibility, growth performance, and health due to its high nutrient content and active substances. It can be seen from Table 2 that alfalfa hay and fresh alfalfa at the initial flowering stage have higher crude protein (CP) content; alfalfa stem, alfalfa meal, and granules have higher neutral detergent fiber (NDF) and acid detergent fiber (ADF) content; and alfalfa grass block has higher crude ash (ASH) content, which can be used as a mineral supplement for ruminants. The production of alfalfa meal can increase the surface area and improve the digestibility and absorption rate of livestock. Compared with other grass products in Table 2, alfalfa meal has higher ether extract (EE) content. Liang et al. (2024) showed that alfalfa meal is rich in protein, vitamins, crude fiber, and other nutrients, and active substances such as saponins and flavonoids. It can promote animal growth, enhance antioxidants, and has immune properties. Chen et al. (2024) indicated that dietary 5% alfalfa meal has no effect on the growth performance of raccoon dogs, but has the potential to increase serum antioxidant capacity and improve intestinal flora.

Bioactive substances of high-quality forage

The main bioactive substances, their locations and extraction methods of alfalfa are shown in Table 3. Flavonoids and other bioactive ingredients in alfalfa have significant application value in animal husbandry, which can not only promote the growth and reproduction of animals but also enhance immunity, improve the quality of animal products, and play an important role, with anti-inflammatory, antibacterial, antiviral, and antioxidant aspects. These findings highlight the importance of alfalfa as a feed additive in modern agricultural practices. Flavonoids in alfalfa, renowned for their multifaceted benefits, are extensively employed as feed additives in animal production. Their incorporation is primarily attributed to their ability to stimulate animal growth and development, thereby enhancing the quality of animal products (Camargo et al., 2021). Recent research by Li et al. (2024) has further illuminated the diverse functionalities of flavonoids, including their anti-inflammatory, antibacterial, antiviral, antioxidant, and immunomodulatory properties. These attributes collectively contribute to improved growth performance, heightened immunity, superior livestock product quality, reduced stress, and effective disease prevention and treatment, underscoring their vast potential in the realm of animal husbandry. Moreover, Qu (2023) have identified flavonoid

TABLE 1 Nutritional composition of alfalfa raw materials.

Breed	Ash, %DM	CP, %DM	EE, %DM	CF, %DM	NDF, %DM	ADF, %DM	Data source
Zhongmu No. 3	7.52	18.72	2.72	35.15	53.71	39.69	(Li Z-M et al., 2020)
Rudo	7.73	22.43	2.82	30.45	46.57	33.77	(Li Z-M et al., 2020)
Aohan	8.36	19.28	2.31	35.58	54.56	40.18	(Li Z-M et al., 2020)
Jinhuanghou	7.87	27.19	2.44	31.70	51.14	36.45	(Li Z-M et al., 2020)
First crop of white alfalfa BHWS2	8.79	26.28	2.10	25.34	ND	ND	(Wang, 2006)
Salt-resistant star	9.25	17.78	1.31	ND	51.40	33.51	(Ni et al., 2019)
WL343HQ	8.98	18.30	1.52	ND	50.54	30	(Ni et al., 2019)
Kangsai	9.01	19.21	1.60	ND	46.54	29.23	(Ni et al., 2019)
Giant 418Q	9.34	17.63	1.34	ND	51.39	32.20	(Ni et al., 2019)
Zhongmu No.1	8.48	17.27	1.31	ND	50.03	30.89	(Ni et al., 2019)

DM, dry matter; Ash, crude ash; CP, crude protein; EE, ether extract; CF, crude fiber; NDF, neutral detergent fiber; ADF, acid detergent fiber; ND, no detected.

TABLE 2 Nutritional composition of several common alfalfa products.

Item	DM (%FM)	CP (%DM)	NDF (%DM)	ADF (%DM)	ASH (%DM)	EE (%DM)
Fresh alfalfa	24	19	46	34	9	3
Alfalfa stems	89	11	68	51	6	1.3
Early bloom alfalfa hay	90	19	45	35	8	2.5
Mid Bloom Alfalfa Hay	89	17	47	36	9	2.3
Alfalfa Silage	30	18	49	37	9	3
Alfalfa Blocks	91	18	46	36	11	2
Alfalfa Meal	89.90	15.20	56.87	44.27	8.28	2.87
Alfalfa Pellets	86.76	16.4	55.42	41.3	9.29	2.8

The data is sourced from the "China Feed Composition and Nutritional Value Table (2020, 31st Edition)" of the China Feed Database. Note: DM, dry matter; Ash, crude ash; CP, crude protein; EE, ether extract; CF, crude fiber; NDF, neutral detergent fiber; ADF, acid detergent fiber.

compounds as pivotal secondary metabolites in alfalfa. Notably, Zhan et al. (2017) reported that the total flavonoid content in 73.3% of 45 alfalfa varieties cultivated in China ranges from 0.6% to 0.9%. The active constituents in alfalfa, when utilized as animal feed additives, exhibit the capacity to augment animal lymphocyte levels, thereby fortifying immunity. Concurrently, they activate glutathione peroxidase, reduce malondialdehyde content, and exert antioxidant effects. Additionally, these compounds have been shown to enhance both the production and reproductive performance of animals, further cementing their significance in modern agricultural practices. Liao et al. (2021) found that alfalfa is rich in polysaccharides, saponins, flavonoids, leaf proteins, and other bioactive components, which can enhance the production performance, reproductive performance, immunity, and intestinal function of livestock and poultry, and significantly improve the quality of their products. Xu et al. (2018) found that alfalfa is rich in non-protein amino acids, organic acids, polyols, alkaloids, carotenes, coumarins, digestive enzymes, flavonoids, phenolic compounds, female plant hormones, phytosterols, polyamines, saponins, and other volatile organic compounds, such as terpenes, furans, alcohols, ketones, and other compounds.

High-quality forage storage and processing technology

Alfalfa processing technology primarily encompasses the production of various hay products, including bales, grass powder, grass blocks, grass bricks, and grass particles, and silage, total mixed ration (TMR), and other feed forms. Furthermore, to ensure optimal growth and yield, the integration of fertilization and irrigation practices in alfalfa cultivation is essential.

Alfalfa planting and cultivation techniques

As can be seen from Table 4, the intelligent water and fertilizer integration model had the optimal production efficiency and economic benefit, ideal for alfalfa irrigation. However, this model has a high investment and a long cycle. Of the other models, such as shallow-buried drip irrigation, sprinkler irrigation, etc., the effect of the flood irrigation model was the worst. From 2017 to 2020, the overall production efficiency was on a downward trend, but the smart mode continued to rise. In terms of economic benefits, the returns of all the models rose, with the largest increase in 2019. Overall, although the intelligent water and fertilizer integration model was superior, it needs to weigh the investment and income (Gao, 2023).

As can be seen from Table 5, the yield and quality of alfalfa were effectively improved by the fertilization amount and the fertilization period. The annual hay yield was the highest with a one-time fertilization of 525 kg· hm^{-2} during the greening period in the cold black soil farming area (Wang et al., 2019).

As shown in Table 6 (Han et al., 2009), under the condition of the same nitrogen fertilizer level, phosphorus fertilizer was applied to two alfalfa varieties, Ameri Stand 201 + Z and Pastoral, and the results showed that the hay yield increased with the increase in phosphorus fertilizer dosage. In the treatment with potassium fertilizer, the yield of Lobo varieties increased by 76.7%. $N_{30}P_{120}$ treatment of Ameri Stand 201 + Z and Ameri Graze 401+ Z had the highest yield, increasing 41.1% and 74% compared with the control, respectively. The content of available phosphorus in alfalfa soil increased with the increase in the amount of phosphorus fertilizer, and the available phosphorus in NPm-treated soil increased by 11.45–41.7 mg/kg. The content of available phosphorus and total potassium increased by 3.71–4.41 mg/kg and 0.06–1.69 mg/kg, respectively.

Alfalfa harvesting and processing technology

There are many forms of alfalfa hay products, such as straw bale, straw powder, straw block, straw brick, and straw granule (Ma et al., 2021). Currently, the primary method of preparing alfalfa is natural drying from the bud stage to the initial flowering stage. Suwignyo et al. (2021) demonstrated that free-mixed feed with 10% alfalfa hay (90% Ladom mix + 10% alfalfa) was the best treatment and had

TABLE 3 Main bioactive substances and existing parts of alfalfa and the extraction methods.

Item	Main distribution	Main component	Extraction method	Main function
Protein and amino acid	Leaf, seed, stem	Seed Proteins、Alfalfa seed Proteins, Alfalfa stem proteins	Heating method, acid-heat method, alkali-heat method, lactic acid fermentation method, etc.	Material metabolism, genetic inheritance, growth and development, tissue repair, disease resistance, etc.
Saponin	Root, stem, leaf, flower, seed	Steroidal saponins, triterpenoid saponins, and steroidal glycosides.	Water extraction, alcohol extraction, ultrasonic-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, and supercritical fluid extraction.	Reduces cholesterol, regulates lipid metabolism, enhances immune system function, and provides antioxidant and anti-inflammatory properties
Flavonoid compounds	Stem and leaf	Flavonols, isoflavones, anthocyanins, apigenin, luteolin, chrysoeriol, tricin, naringenin, methyltricetin, genistin, daidzein, glycitein, genistein, formononetin	Ethanol extraction	Lowers cholesterol; enhances immune function; antioxidation, anti-inflammatory, antibacterial, anticancer, and antiviral properties; protects the liver and cardiovascular system; antiallergic, antidiabetic, and antisenescence properties; protects nerves; and improves osteoporosis
Phenolic acid chemical compound	Stem	Gallic acid, vanillic acid, caffeic acid, proanthocyanidins	Soxhlet extractor for continuous extraction, ultrasonic-assisted extraction, microwave-assisted extraction, column chromatography, and preparative high-performance liquid chromatography (HPLC) techniques to further purify phenolic acid	Acid compounds; anti-inflammatory, antimicrobial, antiviral, and antioxidant properties; and digestive improvement.
Polysaccharides, fibrous substances	Stem	Galactose, arabinose, glucose,xylose	1.Polysaccharides: Ultrasonic-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, alcohol precipitation method、 2.Fibrous substances: Acid-base extraction method, chemical extraction method, enzymatic hydrolysis method, physical method (defatting treatment),	Ensures cardiovascular and intestinal health, cancer prevention, blood sugar reduction, and lowers cholesterol
Vitamin	Leaf	Vitamin A Vitamin E Vitamin C Vitamin B1 (also known as Thiamine) Vitamin B2 (Riboflavin) Vitamin B6 (Pyridoxine) Vitamin B12 (Cobalamin)	Ultrasonic-assisted extraction method, 2,6-dichloroindophenol titration method	Antioxidant properties, prevention of anemia, hemostasis, promotion of bone and dental health, lowers cholesterol, lowers blood sugar, antioxidation, and radiation protection

the highest MA hybrid duck (Mojosari x Alabio) live weight. However, the prolonged duration of the hay drying process renders it vulnerable to the detrimental effects of adverse weather conditions, including wind and precipitation, which can precipitate a significant loss of alfalfa leaves, potentially reaching approximately 30%. Sikora et al. (2021) identified that the primary contributors to storage loss in alfalfa hay are mechanical factors associated with mowing and baling, such as wear and tear. Alfalfa hay, a granular feed derived from the processes of grinding, compressing, and granulating, serves as a nutrient-dense concentrate, characterized by its high protein and fiber content, ease of digestion, and convenient storage. This feed is widely utilized in the realm of animal husbandry. Post-processing, enhancements in starch gelatinization and enzyme activity are observed, which collectively augment the feed's digestibility and conversion rate, thereby significantly boosting the daily gain and overall feed yield for animals. Huang et al. (2011) delineated optimal parameters for alfalfa granulation, with an extrusion force of 5.47 KN, a water content of 16.96%, a grass meal size of 6.34 mm, and a maximum granulation density of 1.241 g/cm^3. Zhang Y et al. (2023) elucidated that high-temperature conditioning augments the processing quality of pellet feed, albeit without a substantial impact on the apparent digestibility of nutrients. They recommended a granulation and conditioning temperature of 90°C for rabbit meat feed. Ban et al. (2024) further contributed to the discourse by

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TABLE 4 The effect of different irrigation models on alfalfa.

Irrigation model	Application effect	Water saving rate (%)	Labor saving rate (%)	Yield increase rate (%)	Water use productivity (kg/m^3)	Production efficiency	Mean Malmquist index	Economic benefit	Multi-year average return(%)
Intelligent water and fertilizer integration model	1	106.63	100	83.04	361.62	1	1.2085	1	173.90
Shallow-buried drip irrigation water and fertilizer integration model	3	ND	ND	ND	ND	2	1.0677	2	84.81
Flood irrigation + water and fertilizer integration model	4	ND	ND	ND	ND	3	0.9828	4	84.16
Flood irrigation model	5	ND	ND	ND	ND	4	0.9811	5	57.52
Sprinkler irrigation, water, and fertilizer integration model	2	ND	ND	ND	ND	5	0.9747	3	42.02

ND denotes not detected.

demonstrating that a grain feed composition, comprising a 1:2 ratio of yellow corn straw to alfalfa green hay and a 50:50 ratio of fine to coarse particles, optimally supports sheep feeding and warrants broader adoption.

The development of alfalfa silage technology

Alfalfa silage is preserved through pit storage and bale silage, helping to maintain the nutritional integrity of alfalfa. Alfalfa pit storage involves a meticulous process of on-site drying, shredding, transporting, compacting, and sealing, ensuring optimal dry matter content. In contrast, bundled silage is produced by shredding alfalfa and forming it into round bales, which are then packaged. These advanced technologies have significantly improved the utilization efficiency of alfalfa and enhanced the economic feasibility of dairy farming. The development of alfalfa silage technology witnessed the integration of semi-dry silage and *Lactobacillus* inoculation technology. Although semi-dry silage is widely used in actual alfalfa production, the incorporation of lactic acid bacteria represents a forward-looking approach; such ensilage innovation not only improves the quality of the silage, but also reduces the loss of nutrients and improves animal performance (Ling et al., 2022; Ergin and Gumus, 2020). The effectiveness of alfalfa silage is affected by a number of factors, including moisture content, the level of added sugar, and the use of microbial and chemical additives. The rational use of additives such as formic acid, inoculants, and enzymes can significantly improve the nutritional value and fermentation quality of silage and improve the digestibility for animals and production capacity (Cai, 2018). An investigation on the effects of various silage additives on mixed alfalfa showed that under different additives, the quality ranking was Medicago silo Sila.MIX> Biomin >Sila-MAX> Taiwan Xiandeli. The effect of Medicago and Sila.MIX was the best, which is a suitable additive for the fermentation of alfalfa silage. It should be promoted and applied in production practice (Li X-X et al., 2020). Appropriate additives can significantly improve the nutrient composition and fermentation characteristics of alfalfa silage. This, in turn, enhances its feeding value and highlights the importance of additive selection in optimizing silage quality. Overall, advances in alfalfa silage technology, including processing methods, technological innovations, and the strategic use of additives, play a key role in maintaining nutritional quality and improving fermentation characteristics. These developments are essential to maximize the nutritional value of alfalfa silage, thereby contributing to the sustainable and efficient production of dairy cows. The logical progression of these technologies from processing to application underscores the importance of continued research and innovation in the field of alfalfa silage technology.

Silage is a simple and effective way to alleviate the feed shortage for ruminants. Compared with making hay, alfalfa silage can reduce adverse environmental impact, simplify production links, save manpower and material resources, facilitate mechanized operation, reduce field losses, and maximize the nutritional value of green feed.

TABLE 5 Effects of fertilizer amount and fertilization period on alfalfa yield.

Fertilization period	Rate of fertilizer application ($kg \cdot hm^{-2}$)	Annual hay yield ($t \cdot hm^{-2}$)	Crude protein content (%)
Alfalfa regreening period	525	12.15	ND
Alfalfa regreening period	450	12.07	23.37 (First cutting of alfalfa)
After the first mowing period	450	ND	25.64 (Second cutting of alfalfa)
After the second mowing period	450	ND	25.40 (Third cutting of alfalfa)

ND means not detected.

Silage alfalfa feed has high palatability, high digestibility, and is suitable for long-term storage to maintain the balance of supply throughout the year. Han et al. (2023) showed that adding fermented alfalfa to livestock and poultry diets could significantly improve production performance, improve animal product quality, and increase economic benefits. Liu (2022) research demonstrated that replacing alfalfa hay with alfalfa silage in the diet of dairy cows resulted in a significant reduction in milk yield. Conversely, substantial increases were observed in milk fat percentage, milk fat yield, and total solids content, with a noticeable upward trend in total solids yield as well. This shift in milk nutritional composition can be attributed to the microbial fermentation that occurs during ensiling, which reduces the forage's energy density and alters ruminal fermentation patterns, promoting greater milk fat synthesis at the expense of overall milk volume production. Nevertheless, the inherent high levels of organic acids, salts, minerals, buffering capacity, dry matter, and water-soluble carbohydrates (WSCs) in alfalfa pose challenges for its long-term storage. To address this, extensive experimentation has demonstrated the potential of enhancing the nutritional value and fermentation quality of alfalfa silage through the incorporation of natural additives such as mulberry pulp, apple, wolfberry leaves (GBL), and whey powder (WP), as well as blending alfalfa with whole corn silage. Şengül et al. (2022) further investigated the impact of dry mulberry pulp WSC on the nutrient composition, pH, and silage acid profile of alfalfa silage. It was found that adding 5% to 7.5% mulberry pulp to alfalfa silage was the most suitable for quality improvement. It is speculated that the high WSC content of dry mulberry pulp makes up for the low sugar in alfalfa. Erişçi et al. (2022) have shown that adding 10% apple to alfalfa silage can improve silage quality. Duru et al. (2023) studied the effects of different levels of GBL on nutrient content, partial fermentation characteristics, dry matter intake, digestible dry matter content, and relative feed value of alfalfa silage. The findings indicate that GBL is efficacious for alfalfa silage, particularly at a 1% dosage, exhibiting positive effects on silage quality. İpçak et al. (2022) demonstrated that the incorporation of WP enhances the total digestible nutrient (TDN) and net energy for lactation (NEL) values of herbage. To achieve superior quality alfalfa hay, WP serves as a viable alternative source of WSCs. Specifically, the addition of 4% whey powder to hay production significantly augments the quality of silage fermentation. Whole corn, rich in non-structural carbohydrates (NSCs), compensates for the nutritional deficiencies in alfalfa silage. Mao et al. (2022), through their investigation of bacterial community dynamics and the effects of different mixing ratios on the fermentation and storage stability of alfalfa and whole plant corn silage, revealed that incorporating at least 20% whole plant corn silage enhances fermentation quality and storage stability. This mixture results in alfalfa silage with a higher proportion of dry matter, TDN (Zhang Y-X et al., 2023), and energy, as well as increased soluble components of CP, NDF, and ADF, while

TABLE 6 The hay yield per crop of the alfalfa varieties with different treatments.

Variety	Treatment (kg)	1st harvest(kg)	2nd harvest (kg)	3rd harvest (kg)	Total yield	Increase (%)
Ameri Stand 201+Z	CK	3,611	1,937	3,763	9,311 cC	ND
	K60	4,298	2,533	5,267	12,098 bB	30.0
	N30P60	4,361	2,852	5,395	12,608 bAB	35.4
	N30P120	4,415	2,690	6,034	13,139 aA	41.1
Ameri Graze 401+Z	CK	2,693	1,303	2,873	6,869 cC	ND
	K60	3,769	2,137	5,022	10,928 bB	59.1
	N30P60	3,868	2,040	5,932	11,840 aA	72.4
	N30P120	4,349	1,939	5,720	12,008 aA	74.8
Lobo	CK	2,325	1,310	2,684	6,319 cC	ND
	K60	2,756	3,272	5,137	11,165 aA	76.7
	N30P60	3,096	1,859	5,301	10,256 bAB	62.3
	N30P120	2,733	2,143	5,014	9,890 bB	56.5

K_{60}, Potassium fertilizer K_2O was applied alone at a rate of 60 kg/hm^2; $N_{30}P_{60}$, Nitrogen and phosphorus were applied in combination at N 30kg/hm^2 and P_2O_5 at 60kg/hm^2; $N_{30}P_{120}$, nitrogen and phosphorus were applied at an increased dosage of N 30kg/hm^2 and P_2O_5 at 120kg/hm^2. ND means not detected. Values followed by different uppercase and lowercase letters within a column mean significant at 1% and 5% levels, respectively.

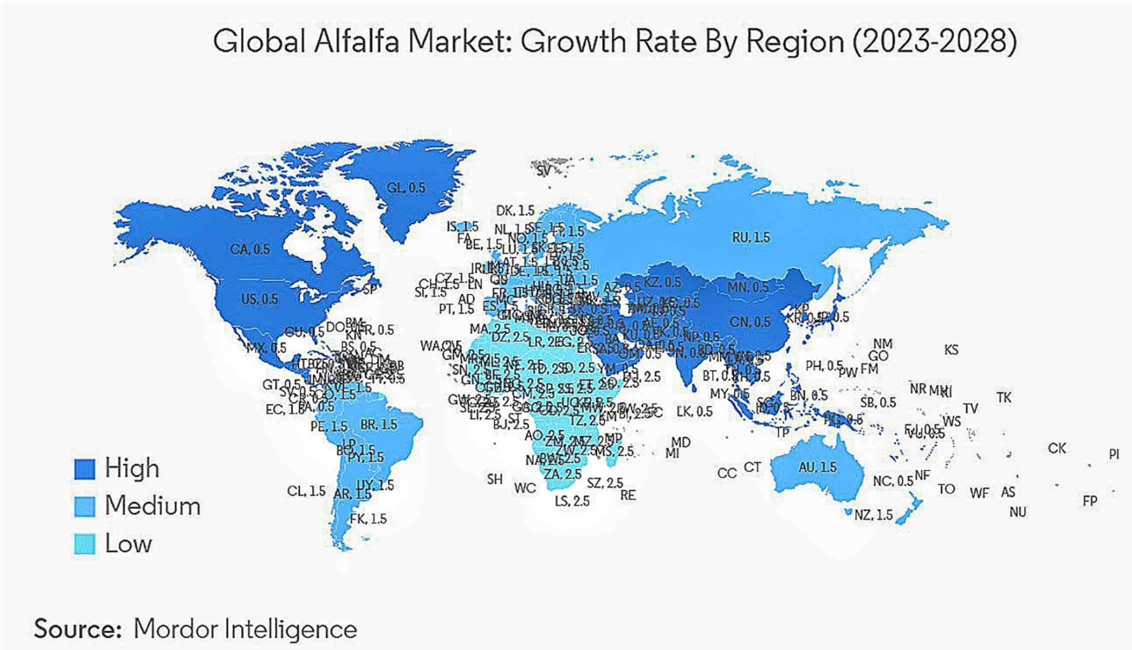

FIGURE 1
Global alfalfa market: growth rate by region (2023–2028). Source: Mordor Intelligence.

concurrently reducing fiber content, thereby facilitating easier digestion. Wang (2023) identified *Bacillus coagulans* BC57 and *Bacillus subtilis* BS21 as promising additives for alfalfa silage, owing to their rapid growth, broad utilization of sugar sources, and robust adaptability to acidic and high-temperature environments. These additives were found to effectively reduce dry matter loss, lower pH, and increase lactic acid (LA) content, thereby improving silage quality. The dominant bacterial genera in low dry matter silage were *Enterococcus* and *Rhabdanaerobium*, whereas those in high dry matter silage were *Weissella* and *Erwiniaceae*. The addition of *Bacillus coagulans* 57 and *Bacillus subtilis* 21 resulted in an increased abundance of *Lactobacillus* and a decreased abundance of *Erwiniaceae*. The highest abundance of *Lactobacillus* was observed in the *Lactiplantibacillus plantarum* 155+BC57 treatment group. A study by Xu et al. (2023) demonstrated that alfalfa silage effectively enhanced meat quality, as evidenced by improved water retention, reduced leakage loss, and a higher marbling score, through the remodeling of intestinal flora and alterations in the content of short-chain fatty acids (SCFAs). Zhang et al. (2022) research shows that 50% fermented alfalfa in an alternative-based diet to fatten pigs can significantly improve muscle amino acids, fatty acids, and other nutrients; significantly improve serum biochemical and antioxidant properties; and promote the health of pork tissue. As the key to the production, processing, and industrialization of alfalfa, silage modulation is a key measure to ensure the maximum preservation of the nutrients of alfalfa, adjust feed supply, and deal with the uneven feed supply. Zhang H-M et al. (2023) showed that the production and processing technology of alfalfa wrapped silage was mature, and the equipment at home and abroad could meet the needs of large-scale production. It can solve the problem of nutrient loss in traditional alfalfa hay processing and reduce production costs. Its feeding value is richer than alfalfa hay and can be used as a substitute for alfalfa hay. Thomas et al. (1969) estimated that the dry matter energy per gram of alfalfa silage is 1.24 times that of the digestible energy of alfalfa hay. Radovic et al. (2009) have shown that the average loss rate of nutrients in the process of hay-making ranges from 30% to 50%, while the loss rate of alfalfa silage is 5% to 20%. Although fewer nutrients are lost during silage, the change in nitrogen composition in alfalfa silage and the effect of microbial fermentation substances on alfalfa cannot completely replace hay (Guo et al., 2024). Yang and Zhang (2023) demonstrated that the fermentation of alfalfa added to feed helps increase milk yield and quality in dairy goats, improves protein utilization, and significantly reduces serum glucose and urea nitrogen levels. Additionally, feeding animals with alfalfa silage instead of other forage grasses can effectively increase body weight and backfat thickness at comparable feeding ages.

In order to reduce the cost of human nutrition supply, eliminate industrial residues, and prevent environmental pollution caused by residue accumulation, it is urgent to study scientific and reasonable forage storage and processing technology and promote agricultural transformation. Koc et al. (2021) have shown that the application of commercial kefir yeast to alfalfa silage can improve fermentation quality and aerobic stability under low WSC content. Both *L. plantarum* MTD/1(*L. plantarum* MTD/1) and L. *buchneri* 40788(L. buchneri 40788) can effectively reduce the distribution of antibiotic resistance genes (ARGs) in alfalfa silage. The silage inoculated with *L. plantarum* ATCC14917 and LP1–4 strains could greatly reduce rumen methane emission. Biosilage combined with laccase and *Cocccoccus pentosacchari* can improve fermentation quality and nutritional value. Muck et al. (2018) found that adding beneficial bacteria, such as *L. plantarum* and *L. buchneri* (LB), in the process of alfalfa silage can reduce pH, reduce protein degradation rate, and inhibit the reproduction of harmful microorganisms. Yang et al. (2022) investigated the effects of wilting and inoculating *L. plantarum* on the fermentation products of alfalfa silage, residual non-structural carbohydrates, and bacterial community dynamics, showed that the high water content of unwilted alfalfa silage led to the rapid consumption of WSCs and the growth of harmful microorganisms in the early stage of silage, resulting in poor fermentation quality. Both wilting and *L. plantarum* inoculation could improve the fermentation quality of alfalfa silage and inhibit the growth of rotting microorganisms, but *L. plantarum* inoculation alone could not achieve the best fermentation quality of unwilted alfalfa silage. Aydin (2023a) added different sources of lactic acid bacteria (LAB) liquid, which is also known as pre-fermented juice (PFJ), to alfalfa silage and some lactic acid bacteria inoculants on fermentation to measure *in vitro* organic matter digestibility (IVOMD) and *in vitro* gas production. It was found that PFJ (3% molasses), prepared from meadow grass 2% molasses in alfalfa, had positive effects on silage quality, fermentation characteristics, and IVOMD. *L. plantarum* A1 (Lp A1), which secretes averolate esterase (FAE), is also a promising silage agent because FAE can alter plant cell wall structures during silage, which is expected to improve feed digestibility. Li F. et al. (2023) have shown that inoculation with Lp A1-producing FAE in silage could effectively improve silage quality and digestibility, regulate rumen fermentation, and improve feed utilization.

High-quality silage can provide excellent nutrition for ruminants, while potential risk factors in the feed, such as ARGs, may have adverse effects on the health of animals. ARGs are a new type of pollutant and pose a major threat to public health. However, the distribution and transmission risk of ARGs in alfalfa silage, which is the main feed for ruminants, has not been studied. Zhang X. et al. (2023) adopted metagenomic methods to reveal the antibiotic resistance of alfalfa silage after inoculation with *L. plantarum* MTD/1 or *L. buchneri* 40788 and found that inoculated *L. plantarum* MTD/1 or *L. buchneri* 40788 alfalfa silage reduced the abundance of ARGs in alfalfa silage by reducing host bacteria and increasing ARGs on the plasmid. The silage effect of *L. plantarum* treatment was better than that of the *Lactobacillus brucei* treatment. The development of alternative antibiotics is essential for the sustainable development of global animal production. Bacteriocins offer advantages such as being non-resistant to drugs, leaving no residues, and being environmentally friendly, and are being considered potential substitutes for antibiotics. Li Z. et al. (2023) studied the effects of *L. plantarum* ATCC14917 and LP1–4 on different DM contents of alfalfa silage inoculated with bacteriogenic inoculants and found that bacteriogenic inoculants had great potential to reduce rumen methane emission, but had no adverse effect on rumen fermentation of inoculated alfalfa silage. Bao et al. (2022) studied the effects of laccase and *Pediococcus pentosaceus* bioenhanced silage on the fermentation quality, nutritional value, enzymolysis and bacterial community of alfalfa, and found that laccase biosilage combined with *P.* pentosaceus is an effective and practical strategy to improve the fermentation and nutrient preservation of alfalfa silage. Seed and pumpkin waste, potato processing industry by-products, and silicon wafer waste are important components of the large amount of industrial waste generated each year and have the potential to be used as livestock feed. Pumpkin waste, unsuitable for human consumption, can be properly treated to reduce agricultural land conflicts between humans and livestock. The research by Das et al. (2023a) indicated that high-moisture pumpkin residue can be used as an alternative source of roughage for ruminants in silage supplemented with wheat straw and alfalfa. Das et al. (2023b) added a by-product of potato chip waste from the potato processing industry to alfalfa with high buffering capacity as an easily soluble carbohydrate source. It was found that the silage prepared by adding 1% debris waste had a positive effect on silage fermentation. Aydin (2023b) studied the effects of adding silicon waste as a soluble carbohydrate source to alfalfa silage on silage quality, fermentation characteristics, organic digestion *in vitro*, and CH_4 value *in vitro* and it was found that silicon waste as a soluble carbohydrate had positive effects on alfalfa silage quality and fermentation characteristics. The addition of sodium diacetate (SDA) improved the fermentation quality, aerobic stability and *in vitro* digestibility of wet hulled barley lees total mixed diet silage.

Guo et al. (2023) identified that functional *Lactobacillus* play multiple roles in silage preparation, including the production of ferulic esterase, antibacterial compounds, antioxidants, pesticide degradation, and 1,2-propylene glycol synthesis, along with low-temperature resistance. In contrast to conventional lactic acid bacteria, functional lactic acid bacteria produce probiotic metabolites that positively influence animal performance, health, and product quality. The metabolic profile of silage reveals a substantial presence of probiotic metabolites, which exhibit antibacterial, antioxidant, aromatic, and anti-inflammatory properties. In the future, LAB can develop silage into fermented feed, as a probiotic transport carrier, and promote animal health and welfare, which has great development potential. Because leguminous and gramineous forages can complement each other when mixed in silage, so as to obtain more excellent silage benefits, the application of *Lactobacillus acetotolerans* isolated from corn (Zea mays *L.*) in alfalfa silage is the most critical, and should be promoted and utilized. Zong et al. (2021) screened seven strains of lactic acid bacteria in silage maize, among which three strains had strong acid production capacity, rapid reproduction rate, and rapid pH reduction rate. Furthermore, 16 SrDNA were identified as *L. plantarum*, which could be used as a candidate strain for silage additives. In addition, alfalfa silage efficiency is also related to the maturity of raw materials and cutting time, the speed of filling into the silage facility, the degree of compaction, the concentration and content of substances such as sealing, acidity, nitrogen, and the type and number of microbial inoculants.

Alfalfa silage supplemented with self-screening lactic acid bacteria has higher sensory and quality levels (Liu Y et al., 2024), methyl benzoate, ethyl benzoate, ethyl salicylate, and other ester compounds with the aromatic odor significantly increased. Adding self-screening lactic acid bacteria to alfalfa silage in carbohydrate metabolism, amino acid metabolism, secondary metabolite synthesis, and aromatic compound metabolism significantly enhanced the function and improved the smell and quality of silage. In the processing of alfalfa silage, the quality and nutritional value of silage can be significantly improved by adding high-quality and low-cost enzyme preparations such as glycolase, phytase, cellulase, and xylanase. Adding lactic acid bacteria and cellulase to alfalfa silage can significantly improve its fermentation quality (Wan et al., 2011), decreasing the content of ammonia nitrogen, preserving more crude protein, and generating more lactic acid. The best silage effect was obtained by adding lactic acid bacteria (106 cfu/g) and cellulase (0.05 g/kg) to alfalfa that was dried for 8h, and the best effect was obtained by direct silage of alfalfa that was dried for 32 h. Liu W et al. (2024) reported that the application of xylanase reduces the viscosity of silage, promotes the fermentation process, improves feed digestibility, and significantly enhances the fermentation quality and nutritional value of silage. Saccharification enzymes can effectively convert starch into fermentable sugars, increasing the energy content and improving the palatability of silage. Additionally, the use of saccharification enzymes can enhance the fermentation quality and nutritional value of silage (Ge et al., 2014). Phytase releases phosphorus and other trace elements by breaking down phytic acid, thereby enhancing the utilization of these nutrients and reducing environmental pollution. The application of phytase can significantly improve phosphorus utilization in silage (Xue et al., 2018). TMRs can extend the storage time of mixed feeds, and alfalfa silage directly provides an acidic environment in fresh TMR, performing similarly to *Lactobacillus* inoculants to improve fermentation quality during the silage process. However, the optimal proportion of silage added to TMR remains unknown. Xie et al. (2022) found that adding 40% alfalfa silage to TMR yields the best results, not only improving fermentation quality but also enhancing resistance to aerobic deterioration.

Application of high-quality forage pellets in production

The stems and leaves of alfalfa contain abundant nutrients and have certain medicinal value, and obvious antibacterial and antioxidant effects. A large number of studies show that it is an effective method to make alfalfa silage. In order to ensure the nutritional quality and fermentation success of alfalfa silage, natural additives such as mulberry pulp, apple, wolfberry leaves and whey powder have been commonly used (Zhang et al., 2015; Zhang, 2022). To improve the quality and efficiency of silage, a comprehensive approach can be adopted, which combines multiple raw materials and additives. Firstly, through waste utilization, materials that might otherwise be discarded, such as seed pumpkin waste, potato processing by-products, and silicon wafer waste, are effectively utilized. Secondly, by using lactic acid bacteria, enterococcus, *Bifidobacterium* and other functional lactic acid bacteria, such as commercial kefeles yeast, lachinase, streptococcus pentose, and self-selected *Lactobacillus plantarum* MTD/1(L), these microorganisms contribute to the fermentation process and improve the quality of silage. In addition, when mixing leguminous and gramineous forage grasses for silage, high-quality and low-cost enzyme preparations such as glycolase, phytase, cellulase, xylanase and amylase are added. These enzymes can break down complex carbohydrates, release more nutrients, and improve the digestibility and utilization rate of silage feed. Through this comprehensive approach, the various components complement each other's advantages, which can significantly enhance the overall effect of silage feed, achieving better silage fermentation and higher nutritional value. In animal production, alfalfa as a raw material for silage has been proven to have no adverse effects (Lafreniere et al., 2021), and in some countries and regions not suitable for silage corn growth, alfalfa silage has become a substitute for corn silage (Borton et al., 1997). However, the high content of cellulose in alfalfa may affect its fermentation quality and nutrient retention during silage. Therefore, the development and utilization of alfalfa silage requires further research and optimization. In addition, silage pellet feed has a broad development prospect in practical production, but its processing and modulation methods still need to be further studied and popularized.

Author contributions

S-YW: Writing – original draft, Conceptualization, Formal Analysis, Investigation, Methodology. YZ: Conceptualization, Writing – review & editing. Z-NH: Data curation, Writing – original draft. Y-YJ: Investigation, Writing – review & editing. LS: Data curation, Writing – original draft. G-LY: Investigation, Writing – original draft. BL: Writing – review & editing. FG: Supervision, Data curation, Funding acquisition, Writing – review & editing.

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Conflict of interest

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

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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