Reducing the Climate Impact of Ruminant Feed and Improving Animal Health in Europe by Using Maize and Lupine Additives

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Ruminant farming is a significant contributor to global food production but also a major source of methane emissions. It is responsible for nearly 44% of greenhouse gases from the agricultural sector. The integration of maize and lupine into the diets of ruminants offers a sustainable strategy for improving feed efficiency, reducing methane emissions, and enhancing animal productivity. Fermented maize silage has been shown to lower methane emissions by 10 to 20% compared to conventional high-starch diets. Lupine supplementation can further reduce methane emissions by influencing rumen fermentation. The inclusion of lupine, a nitrogen-fixing legume, additionally enhances soil fertility and reduces the need for synthetic fertilizers, making it an environmentally sustainable alternative to soybean meal. Studies indicate that diets incorporating maize silage and lupine can improve feed conversion efficiency and increase milk yield by up to 5% in dairy cattle. However, large-scale adoption of these feed additives requires further research to optimize fermentation processes, ensure economic feasibility, and overcome regulatory barriers. This study highlights the potential of maize and lupine as viable solutions for enhancing livestock sustainability while mitigating climate impacts.

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INTRODUCTION

Meat production has more than tripled since 1960, with per capita consumption rising from 23.1 kg in 1961 to 42.2 kg in 2011. In developing countries, pork consumption in particular has surged (Sans and Combris 2015; FAO *et al.* 2022). Highly developed countries have access to various kinds of meat, in quantities far exceeding demand. However, socioeconomic factors have a significant influence on dietary patterns across populations, shaping food accessibility and consumption habits. Individuals with higher socioeconomic status (SES), often indicated by higher incomes and education levels, tend to consume diets richer in fruits, vegetables, and dairy products, while limiting their intake of sugary beverages and energy-dense foods. Conversely, people with lower SES face barriers such as financial constraints and limited access to healthy foods, leading to diets higher in processed and calorie-dense items. Studies indicate that adherence to healthier diets is more prevalent in regions with higher gross domestic product and among families with elevated SES. Such is the case, for example, in Poland. However, this correlation does not always hold. For instance, in urban Burkina Faso higher income and urbanization correlate with a more "western" diet dominated by energy-dense and processed foods. These findings highlight the complex interplay between socioeconomic factors, dietary choices, and global food distribution, emphasizing the need for targeted nutritional interventions that address economic and educational disparities (Nago *et al.* 2012; Mayen *et al.* 2014; Czarnocińska *et al.* 2020; Vilela *et al.* 2014; Weil *et al.* 2023).

The UN estimates that the global population will exceed 10 billion by 2050, with 8% of people expected to suffer from hunger by 2030. These projections highlight the increasing pressure on global food systems. The outbreak of the COVID-19 pandemic and the post-pandemic reality created further challenges for food producers. Many food producers were unprepared for the abrupt upheaval and suffered financial losses from the market shock, including the disruption of supply chains and the food and energy markets. The Russian-Ukrainian war has exacerbated global food insecurity, disrupting supply chains and increasing living costs, adding further challenges to the post-pandemic market (Rowan and Galanakis 2020).

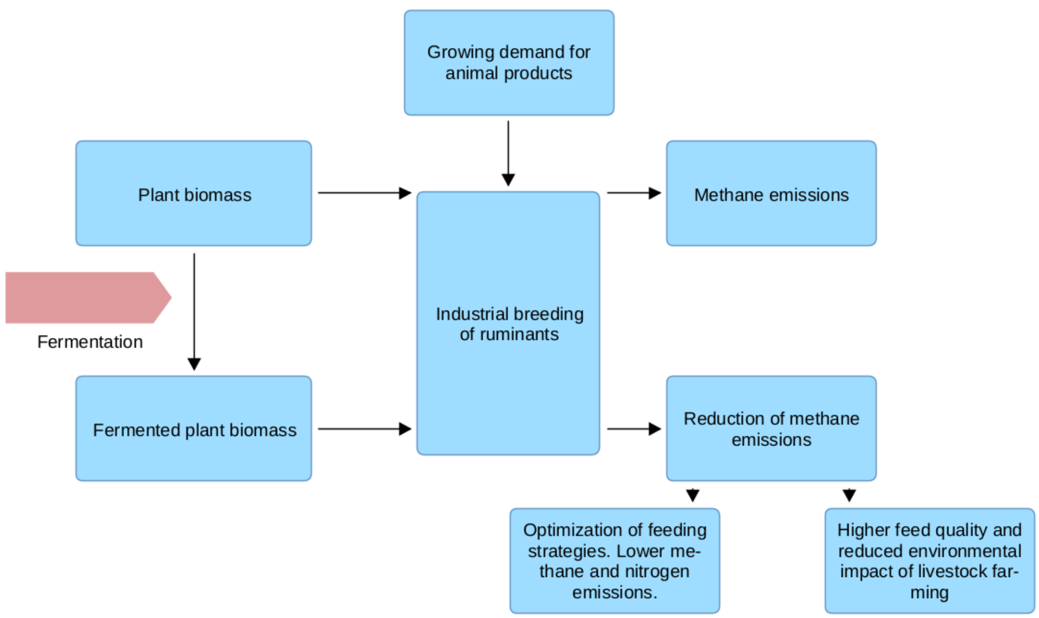

Fig. 1. Role of industrial animal breeding and plant biomass in reducing greenhouse gas emissions

Integrating alternative feed components such as maize and lupine is essential in order to address these global challenges, promoting both the nutritional efficiency of ruminant diets and the sustainability of livestock production systems. Current ruminant feeding strategies rely heavily on energy-rich feeds, such as maize, and protein sources such as soybean meal. However, these conventional approaches have several limitations. Maize-based diets, while providing high energy through starch, often lack sufficient protein, leading to suboptimal nitrogen utilization and increased excretion of nitrogenous waste (Van Soest 1994). Additionally, high-carbohydrate diets contribute to ruminal methane emissions, which not only reduce feed efficiency but also have significant environmental consequences (Beauchemin *et al.* 2008). The dependency on soybean meal for protein supplementation further exacerbates sustainability concerns, as soybean cultivation is associated with deforestation, land degradation, and fluctuating global prices (Lucas *et al.* 2015). Addressing these challenges requires the integration of alternative feed components that enhance both nutritional efficiency and environmental sustainability.

Lupine, a nitrogen-fixing legume, offers a promising alternative protein source that can complement maize-based diets. Its high protein content and favorable amino acid profile improve ruminant nitrogen utilization, potentially reducing the need for external protein supplements (Lucas *et al.* 2015). Unlike soybean, lupine cultivation is not linked to deforestation, and its ability to fix atmospheric nitrogen can enhance soil fertility and reduce dependency on synthetic fertilizers (Van Soest, 1994). Studies suggest that feeding lupine to ruminants may help modulate rumen fermentation patterns, reducing methane production compared to high-starch diets (Eugène *et al.* 2004). Integrating lupine into ruminant feed formulations alongside maize could therefore enhance production efficiency while contributing to more sustainable livestock management practices.

Industrial Animal Breeding

The growing demand for animal products challenges sustainable development, health, and the environment. Livestock production, especially ruminant farming, contributes to methane emissions and antibiotic resistance. Animal farming also puts pressure on vital resources, including water and land. There is also growing criticism of animal husbandry on ethical grounds. For instance, the Montreal Declaration (The Montreal Declaration on Animal Exploitation, 2022) argues for ending all forms of animal farming and exploitation, emphasizing that animals are sentient beings and should not be treated as commodities. Researchers highlight that even high-welfare farms cause suffering due to selective breeding for maximum productivity, making truly ethical farming economically unfeasible. These perspectives suggest that shifting towards plant-based and lab-grown alternatives may be a more ethical and sustainable solution. In response to such criticism, "The Dublin Declaration of Scientists on the Societal Role of Livestock" (2023) gathered international scientists' views on animal and human health, environmental impacts, and socio-economic factors. The Declaration highlighted that humans have evolved to consume both meat and plants, and an abrupt end to animal husbandry would harm the economy, food security, and environmental goals. The Declaration further argues that ethical discussions should prioritize human welfare over animal welfare. As others have noted, animal farming composes up 40% of agricultural output in Europe, with some practices benefiting carbon sequestration, water quality, and biodiversity (Guyomard *et al.* 2021).

Hristov *et al.* (2013) suggest that the most effective strategy to reduce methane emissions from ruminants would be to maximize individual animal productivity, thereby reducing the overall number of animals while maintaining production levels. While intensive feeding increases methane emissions per animal, it ultimately leads to lower total methane emissions compared to conventional feeding practices spread across a larger population. Improving animal health can also reduce the need for antibiotics. Maintaining optimal animal health and producing high-quality animal products relies largely on diet management. Advances in animal nutrition have considerably improved animal health and well-being. Moreover, the exigencies of climate change have driven breeders to adopt more environmentally-friendly and ethical breeding practices. Fodder is the primary feed in animal husbandry, and accounts for nearly 70% of total animal production costs. Effective uptake and utilization of fodder by animals not only can reduce costs but also it can decrease their greenhouse gas emissions. Feed efficiency is indicative of feed quality, reproductive efficacy, health, and management. The optimization of feed with the appropriate nutrient profile and feed additives can contribute to increase the profitability of animal production. This strategy is increasingly important in contemporary production systems.

Global animal production is regulated by numerous standards and regulations that individual countries issue on the basis of recommendations and research carried out by the FAO, which operates as part of the United Nations. The European Union (EU) has established some of the most comprehensive and stringent standards for food and agriculture, particularly emphasizing animal health and welfare (AHW). These EU standards have been supplemented by private AHW standards, which aim to increase and maintain quality while adhering to social and ethical criteria. Private AHW standards are often even more restrictive, and their presence has significantly improved the animal industry (More *et al.* 2021). Consumer perceptions and concerns about the health and welfare of farmed animals also play a crucial role, influencing their purchasing decisions regarding animal products.

BREEDING OF RUMINANT ANIMALS

Human-farmed ruminants are the largest consumers of plant biomass in the world, consuming approximately 4.85 billion tons of biomass per year. Due to their ability to digest plant fiber and ferment it in the rumen, ruminants are able to feed on almost any type of plant. As a result, humans have long used ruminants to transform plants, especially carbohydrates, into high nutritional value milk and meat. Ruminants are also producers of organic fertilizers, which are extremely valuable in regions with poor access to chemical fertilizers and unfavorable conditions for growing plants (Faverdin *et al.* 2022). Over 50 million years of evolution, there have been many changes not only in ruminant organisms, but also in the nature of their symbiosis with microorganisms inhabiting their digestive tracts, which can be treated as a very specific type of bioreactor. The rumen microbiota play a very important role in converting plant materials that are inaccessible to animals into nutrients. Various species of microorganisms are responsible for the digestion of complex carbohydrates (Gonzalez-Recio *et al.* 2023). The rumen ecosystem is a classic example of host-microbiome symbiosis. This relationship is based on the consumption of plant fibers by the host which it is unable to digest. These indigestible plant fibers can be degraded only through metabolic processes (hydrolytic and fermentative reactions), by microorganisms colonizing the animal's digestive system. The symbiosis of ruminants with microbiota influences animal phenotypes, including feed efficiency and methane emissions, suggesting potential for reducing methane emissions and improving feed processing (Morais and Mizrahi 2019).

A very important factor determining the health and welfare of animals in later life is the morphological development of the rumen in young ruminants. The morphological development of the rumen depends on the production and absorption of volatile fatty acids (VFA), which stimulate the growth of the rumen nodules, affecting the possibility of further metabolic processes. In turn, the physical form of the feed affects the development of muscles, stimulates the chewing mechanism, and increases the flow of saliva. The development of the rumen in young ruminants is favored by the consumption of solid fodder. The capacity of the rumen must develop as the animal grows, because more than 60% of all VFA and more than 75% of butyrate is absorbed through the rumen epithelium. Recent studies have shown that the rumen of a weaned calf contains the same dominant Bacteroidetes, Firmicutes, and Proteobacteria clusters as the mother, but in variable amounts depending on the timing of the introduction of solid feed into its diet (Cheng *et al.* 2021).

An important characteristic of feed intended for ruminants is the residence time in the rumen, which affects the use of feed by microorganisms that can break it down and ferment it. The main sources of energy for microorganisms are carbohydrates, peptides, and amino acids, which are used in the processes of transamination and deamination (Cheng *et al.* 2021). Ruminant animals need only five key nutrients: crude protein, energy (in the form of fiber), fats, and water-soluble vitamins and minerals (McGrath *et al.* 2018). Longer residence time is conducive to the effective slow fermentation of plant fibers. The rate and productivity of protein synthesis depends on the microorganisms present in the rumen and in the food. This makes it very difficult to optimize the amount of protein supplied to the ruminant, because most of the proteins that are digested by ruminants in the small intestine are rumen-derived microbial proteins, production of which depends on fermentation efficiency. Compared to monogastric animals or poultry, this complicates the supply of appropriate amounts of amino acids, because protein digestion in monogastric animals and poultry occurs earlier in the digestive system, before the fermentation process (Moorby and Fraser 2021). Dijkstra *et al*. (2013) suggest that ensuring the optimal supply of nitrogen will improve the efficiency of protein synthesis, because this will prevent too much nitrogen being used by microorganisms living in the rumen.

It has been estimated that ruminants are responsible for 14.5% of global greenhouse gas (GHG) emissions, with nearly 44% of these emissions consisting of methane. Methane is produced by microbial fermentation in the digestive system and is emitted in significantly larger quantities by ruminants than by monogastric animals. The Intergovernmental Panel on Climate Change (430) Sixth Assessment Report (2023) mentions that agriculture, forestry, and other land use (AFOLU) sectors contribute approximately 22% of global GHG emissions. The report highlights enteric fermentation from ruminants as a major source of anthropogenic methane, potentially accounting for up to 27% of global methane emissions. Animal husbandry also contributes to nitrous oxide emissions, due to the large amounts of manure produced and the nitrogen used in animal feed production. Excreted nitrogen enters the soil and groundwater, leading to pollution and ammonia emissions, which together with other nitrogen oxides contribute to the formation of secondary particulate matter, significantly degrading air quality. The meat industry thus significantly contributes to environmental challenges (Moorby and Fraser 2021).

Recent research has identified several dietary interventions that effectively reduce methane emissions from ruminants. A meta-analysis by Pepeta *et al.* (2024) evaluated various dietary strategies, including the use of nitrate, saponin, oils, biochar, and 3-nitrooxypropanol (3-NOP). These additives were found to effectively mitigate enteric methane emissions, with oils and 3-NOP also enhancing production parameters in ruminant livestock. Notably, 3-NOP has been shown to reduce methane emissions by up to 39%, depending on factors such as dosage, diet composition, and animal type. Additionally, altering the dietary content of non-fiber carbohydrates (NFC) and neutral detergent fiber (NDF) has been demonstrated to decrease methanogen populations and methane emissions by influencing hydrogen production, dry matter intake, and nutrient digestibility. These strategies offer promising avenues for reducing the environmental impact of ruminant agriculture (Lind *et al.* 2023).

Methane reduction by feeding animals fermented feed may be an alternative or complement to the strategies described by Papeta *et al.* (2023). Fermented feed, such as silage, affects the composition of the rumen microbiome, which can lead to reduced methane production. The process of fermenting feed often improves its digestibility and changes the fatty acid profile, which can limit the availability of hydrogen to methanogens and thus reduce methane emissions. Studies indicate that the type, quality, and composition of fermented feed can significantly affect methane reduction. An example is high-starch silage, which can shift fermentation towards the production of propionate instead of methane. Certain additives to fermented feed, such as probiotics or plant extracts, can further modulate the rumen microbiome and reduce methanogenesis (Indugu *et al.* 2024; Nedelkov *et al.* 2024).

Industrial Cattle Breeding

Cattle are one of the largest consumers of plant biomass, and their numbers are growing steadily. Recent decades have seen the specialization of cattle breeds, thanks to which milk production and carcass weight for slaughter have increased. The improvement of animal feeding systems has significantly increased production efficiency and reduced farming costs, with lower feed consumption and emissions of greenhouse gases, including methane (Faverdin *et al.* 2022). There are significant differences in the production of dairy cattle and beef cattle. An expert study involving 70 cattle welfare specialists by Mandel *et al*. (2022) compared common dairy and beef production systems around the world. Animals reared in dairy systems (whether for milk or meat production) were found to be at higher risk of negative welfare status than animals in beef production systems (*i.e.* reared exclusively for their meat), for all animal categories. Contrary to popular belief, this suggests that the consumption of dairy products that contributes more significantly to difficulties in maintaining the health and welfare of animals.

An effective way of breeding dairy cattle is the TMR (Total Mixed Ration) system. TMR is a dairy cow feeding system in which all roughage, concentrates, minerals, and other additives are mixed together and delivered as a complete feed. Animals must have access to the mixture 24 hours a day. The advantages of the system include: increasing feed dry matter intake by almost 2 kg; improving digestibility and feed efficiency by 3 to 5%; increasing milk yield by approx. 5%; and improving the reproduction rate and the possibility of using waste biomass as feed, which contributes to reduce breeding costs. This system has a positive effect on changes in the rumen, maintaining a stable pH, reducing the risk of acidosis and other digestive disorders, and promoting an even course of digestion. The practice of using a mixture of dry and wet feed, including fermented feed, is also an effective method of preserving biomass (Zhang *et al.* 2020). Dairy cows have been shown to excrete almost 75% of the nitrogen they consume, rather than converting it into milk. However, this value decreases if the animal is fed a food with well-balanced nutritional values, including a higher protein content that significantly exceeds its needs (Moorby and Fraser 2021). The herd system, where dairy cows and beef cows are not combined, has been found to be the most efficient system for breeding cows for meat. This system reduces feed consumption and methane emissions (Faverdin *et al.* 2022).

Industrial Sheep and Goat Breeding

The number of sheep and goats in the world is estimated at about 2.3 billion. The number of sheep is slightly higher than the number of goats. These values remain constant, due to the constant demand for sheep and goat dairy and meat products. Sheep are mainly reared in Europe, the Mediterranean, Asia, and the Sahel region of Africa (35 to 55° north latitude), as well as South America, Australia, and New Zealand (30 to 40° south latitude). India and South Africa have also become significant sheep farmers in recent years. Goats are raised in similar regions to sheep, as well as in India and South and Central America (mainly Mexico and Brazil). In Europe, the numbers of sheep and goats have decreased significantly over the last decade, and milk yield has increased compared to meat yield. The number of small ruminants, however, has increased in Asia and Africa, accounting for more than two-thirds of the world's meat and milk production on major local markets. Major sheep and goat farmers in Asia and Africa focus mainly on milk and dairy production, while farmers in Oceania are focused on meat production (Simoes *et al.* 2021).

Historically, sheep farming around the world has been conducted in areas unsuitable for growing crops. The poor quality of the soil and poor vegetation in pasture areas significantly limit the availability, quantity, and quality of food for sheep. Goats, on the other hand, are reared in arid and semi-arid areas and mountainous regions. With the growing demand for animal products since the mid-nineteenth century, breeding methods have changed significantly. The mechanization of breeding and genetic improvement of breeds have enabled the intensification of production while reducing costs. Monitoring the health of sheep and goats aims to eliminate infectious and zoonotic diseases, ensuring animal welfare, food safety, and minimal environmental consequences concerning chemical residues and pathogen circulation. These changes were introduced first in developed countries and then transferred to less developed countries (Simoes *et al.* 2021).

Several factors must be considered when managing the production efficiency of small ruminants—including nutrition, reproduction, and health—in alignment with sustainable development principles. These include seasonality, the breed, and the farm's geographical latitude. High-yielding ruminants have very high nutritional requirements, and their diets must be rich in specific nutrients. Feed profoundly influences animal health and the quality of derived products. The composition of their diets directly impacts the animals' health, immunity, and reproductive capabilities. Expenditure on feed is the main cost associated with sheep and goat farming. The feed type chosen also has environmental implications.

PLANT BIOMASS AS A FEED COMPONENT

According to EU regulations (European Union 2002), feed is defined as "substances or products, including additives, whether processed, partially processed or unprocessed, intended to be fed to animals". Feed additives, which are defined as "substances, micro-organisms or preparations, other than feed material and premixtures, which are intentionally added to feed or water for performance purposes" (European Union 2003), are an important part of the livestock diet. The main purpose of converting plant biomass into feed is to increase the availability and use of plant starch by animals (McGrath *et al.* 2018). Over 1,171 million tons of feed are produced in the world, of which 8% is used to feed ruminants (Fig. 1). The main producers include China, the

USA, Brazil, and EU countries. Global commercial feed production generates an estimated annual turnover of over $400 billion (International Feed Industry Federation 2021).

By-products from the production of food and fuel for humans, such as distillers' grains or rapeseed cake, are often used in the production of animal feed. Producing feed from post-industrial residues that are not edible by humans reduces competition between human food and animal food. The population of microorganisms in the rumen allows for more effective use of nutrients present in plant by-products than in the case of monogastric animals. Some plant by-products are rich in bioactive compounds, including vitamins, unsaturated fatty acids, and antioxidants, the presence of which in the ruminant diet affects the quality of milk, meat, and meat products intended for human consumption (Salami *et al.* 2019).

Fermented food containing probiotic microorganisms improves the health and welfare of animals and ensures higher quality and safer animal products intended for human consumption. Residues from growth promoters and antibiotics administered to animals in milk are a potential threat to consumers. In the case of ruminants, the microorganisms most commonly used for fermentation are those naturally inhabiting the rumen (Puniya *et al.* 2015). Good sources of biomass for feeding ruminants that can also be fermented effectively include maize and yellow or narrow-leaved lupins.

Incorporating corn silage and lupin supplementation into ruminant diets has been shown to influence methane emissions and animal welfare. Corn silage can reduce methane emissions by 10 to 20%, depending on factors including its maturity and the type of feed it replaces. Younger corn plants, which have higher soluble sugar content, promote more efficient fermentation, which may contribute to lower methane production. Additionally, proper ensiling techniques, including the use of *Lactobacillus* strains as inoculants, can enhance silage quality, improve digestion efficiency, and potentially reduce methane emissions. Supplementing ruminant diets with *Lupinus angustifolius* seeds has likewise been found to impact rumen fermentation dynamics. *In vitro* studies indicate that while lupin supplementation increases total gas and methane production, it also enhances nutrient degradation, suggesting that it may function as a beneficial feed additive to support rumen microbial activity and overall digestive efficiency. The overall effectiveness of these strategies in mitigating methane emissions depends on multiple factors, including diet composition, silage processing, and preparation methods. Therefore, further research is necessary to better understand the underlying mechanisms influencing methane production and to optimize feeding strategies for improved sustainability and livestock productivity (Evans 2018; Morsy *et al.* 2024; Villagrasa and Diaz 2020).

The fermentation of maize silage and lupine-based feeds relies on specific microbial communities that optimize nutrient utilization. Lactic acid bacteria (LAB), particularly *Lactobacillus plantarum, Lactobacillus buchneri*, and *Pediococcus pentosaceus*, are commonly used as silage inoculants. These microorganisms facilitate lactic acid production, which lowers the pH of the silage and prevents spoilage, thus preserving starch and fiber digestibility. Ensiling maize with LAB inoculants has been found to increase volatile fatty acid production in the rumen, leading to improved energy absorption and reduced methane emissions. Similarly, lupine interacts with rumen microbial populations, particularly fiber-degrading bacteria such as *Fibrobacter succinogenes* and *Ruminococcus flavefaciens*, enhancing the breakdown of complex carbohydrates and increasing protein availability (Villagrasa and Diaz 2020).

Beyond silage fermentation, the bioactive compounds present in lupine also influence rumen fermentation dynamics, altering microbial activity and volatile fatty acid profiles. Lupins contain alkaloids, which can affect the rumen microbiota composition by modulating populations of methanogenic archaea, thereby influencing methane production. However, processing methods such as thermal treatment or dehulling can reduce alkaloid content, making lupins more digestible and safer for livestock consumption (Morsy *et al.* 2024). Other studies indicate that the supplementation of ruminant diets with lupine seeds enhances nitrogen utilization efficiency by promoting microbial protein synthesis, reducing nitrogen losses, and minimizing environmental impact (Evans 2018). Given these findings, further research into the interactions between maize, lupine, and rumen microbial communities could lead to the development of precision feeding strategies aimed at optimizing fermentation processes while mitigating methane emissions.

Maize in Ruminant Feeding

Maize (*Zea mays*) is a widely cultivated grain that has been safely consumed by humans and animals for centuries. Maize is playing an increasing and diverse role in global agrifood systems. Global maize production has been increasing, in response to increasing demand and thanks to technological progress. Global corn production is 1137 million tons (dry grain). Over the past decade, global maize production has experienced a significant increase. In 2023, the worldwide production of primary crops reached 9.9 billion tonnes, marking a 27 percent rise since 2010. This growth was notably driven by an increase in maize output, which, along with wheat and rice, accounted for 91 percent of total cereal production in 2023 (FAO, 2024). In the last 25 years, yields have increased by more than 50%, while there has been a 46% increase in the cultivation area. Yields of maize have increased more than yields of any other cereals (including wheat and rice) (Erenstein *et al*. 2022).

Corn is one of the most energy-dense foods used for animal production, due to its relatively high protein (10%), fat (4%), and starch (72%) contents. This contributes to high-performance fermentation processes, which are a popular method of preserving corn. Pickling prevents the development of pathogens, including fungi of the genus *Fusarium* and *Aspergillus*, which produce mycotoxins that are dangerous to health. Pickling is also four times cheaper than drying. Properly produced maize silage should meet the following parameters: dry matter content: 30 to 35%; starch content: minimum 30% in dry matter; crude fiber content: maximum 20% in dry matter; ADF (acid detergent fiber) content: maximum 25% in dry matter; NDF (neutral detergent fiber) content: maximum 45% in dry matter (Płacheta *et al.* 2022). It has been shown that feeding cattle with feed containing fermented maize improves the fermentation of feed in the rumen, increases the digestibility of nutrients, and raises efficiency of lactation as well as utilization of nitrogen intake. The use of fermented feed is also more economical. The income from animal production using fermented feed is higher than the cost of the feed (Table 1) (Zhang *et al.* 2020).

Lupine in Ruminant Feeding

Currently, lupine occupies a niche market. It is primarily utilized in specific food products and as a rotational crop in sustainable farming systems. However, lupine offers a potential alternative to soybeans in the production of feed, due to its lower cultivation requirements, low growing season, and additional environmental benefits as a green fertilizer. Global lupine production in 2020 was 1.05 million tonnes. Soybean production was far higher, reaching over 350 million tonnes. Economically, soybeans dominate the global market, due to their extensive use in food products, animal feed, and industrial applications, leading to higher profitability and market demand. Environmentally, however, soybean cultivation has been associated with significant deforestation, particularly in the Amazon region. In Mato Grosso in Brazil, a recent legislative change overturned the Soy Moratorium—a policy that previously curbed Amazon deforestation linked to soy farming. This could potentially lead to increased deforestation rates. Lupine, in contrast, offers several environmental benefits. As nitrogen-fixing plants, they enhance soil fertility and reduce the need for synthetic fertilizers, Moreover, they are typically grown in areas not associated with deforestation pressures (Foodstruct 2024; Siddiqua *et al.* 2023). The most commonly used varieties of lupine used for the production of animal feed are narrow-leaved lupine (*Lupinus angustifolius*), commonly referred to as sweet lupine, and yellow lupine (*Lupinus luteus* L.).

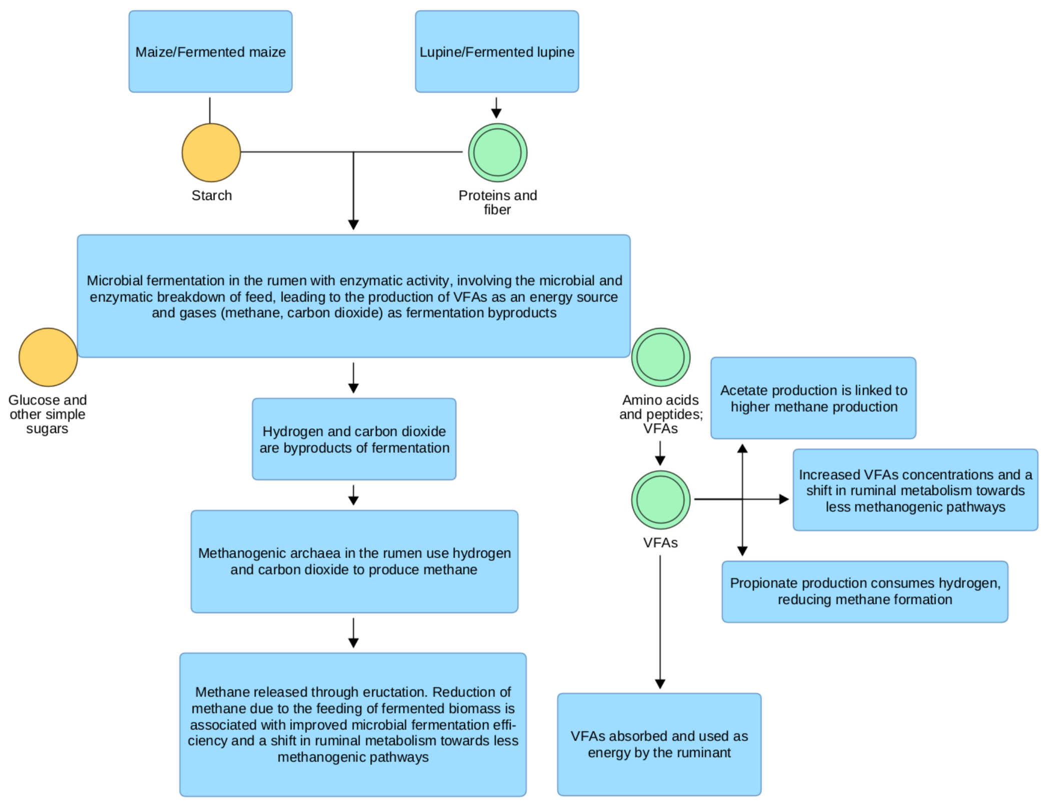

Fig. 2. Biochemical pathways of maize and lupine digestion in ruminants

Lupine seeds are characterized by a high content of crude protein (up to 40% in yellow lupine seeds), a favorable amino acid profile, and high content of carbohydrates (40%) and fat (6%). Sweet lupine is preferred as feed for ruminants, because it is lower in alkaloids. Yellow lupine is richer in anti-nutritive substances (alkaloids, phytates, oligosaccharides), which may have negative effects on the health of animals. Alkaloids, specifically quinolizidine alkaloids, contribute to the bitterness and toxicity of some lupine species, while phytates inhibit mineral bioavailability. Various processing methods have been explored to mitigate the effects of these compounds, enhancing the safety and nutritional quality of lupine-based products. Alkaline thermal processing has been found to be particularly effective, as treating lupine seeds with an alkaline solution under heat significantly reduces the quinolizidine alkaloid content, as well as lowering the content of tannins and phytic acid. Traditional soaking and cooking methods have also demonstrated success, with extended soaking (up to 72 hours) combined with boiling substantially lowering alkaloid levels, making lupine seeds more suitable for human and animal consumption. Biological processes such as fermentation and germination have also been shown to be effective at reducing anti-nutritional factors in lupine seeds. Fermentation, particularly when performed before boiling, leads to a pronounced reduction in alkaloid content, enhancing both digestibility and safety. Similarly, germination triggers enzymatic activity that breaks down phytates, improving mineral availability and the overall nutritional profile of lupine-based foods. These processing techniques not only improve the edibility of lupine seeds but also enhance their potential as a sustainable and nutritious food source (Habtie *et al.* 2009; Mahmoud *et al.* 2016; Mohammed *et al.* 2016).

Lupine silage contains much more protein than maize silage. Although it is a valuable protein feed, the relatively high protein content and low sugar content of lupine silage are not conducive to fermentation (Płacheta *et al.* 2022). Feeding ruminants with fodder with the addition of lupine increases the amount of fatty acids, and it also reduces the production of acetates and methane (Table 1). Lupine seeds are increasingly used as a protein supplement in ruminant diets.

The Economic Feasibility of Maize and Lupine Compared to Soybean Meal or Alfalfa

Soybean meal (SBM) is one of the most commonly used high-protein feed ingredients, but its high price and dependence on imports encourage the search for alternative protein sources. In this context, it is worth analyzing the economic potential of maize and lupine as substitutes for SBM and the possibility of increasing their nutritional value through fermentation. From an economic perspective, maize is generally cost-effective and widely available, whereas lupine's limited cultivation can increase its market price (Lucas *et al.* 2015). Similarly, soybean prices are subject to fluctuations in global markets (Borreani *et al.* 2018). The selection of feed ingredients must balance economic feasibility with nutritional efficiency and environmental sustainability.

Soybean meal has a high protein content (approximately 44 to 48%) and a favorable amino acid profile, but its production in Europe is limited. Most soybean meal is imported, making it susceptible to price fluctuations and GMO-related restrictions (European Commission, 2023). In contrast, maize and lupine can be produced locally, allowing for greater price stability and independence from external markets. Maize is widely cultivated in Europe, especially in warmer regions such as France, Germany, Poland, and Hungary. However, it has a relatively low protein content (8 to 10%), limiting its use as a primary protein source in feed. Lupine, depending on the variety, contains between 30% and 40% protein, making it a potentially valuable alternative to SBM. However, the presence of anti-nutritional factors such as alkaloids can limit its digestibility and nutrient absorption. Maize cultivation is constrained by thermal requirements. The best yields are obtained in regions with a long growing season and high temperatures. In Northern Europe, the shorter growing season and lower temperatures may negatively affect yields. Lupine, on the other hand, thrives in cooler climates and sandy soils but is susceptible to diseases such as anthracnose, which may limit its production in wetter regions of Western Europe (Gulisano *et al.* 2022).

Table 1. Characteristics and Selected Methods of Producing Fodder for Ruminants Using Maize and Lupine as Feed Components

Type of biomass	**Characteristics of the Applied Method**	**Efficiency of the Applied Method**
Maize silage (Legnowski *et al.* 2016)	The feed consisted of 52% concentrate and 48% CS (corn silage), fed to 3 lactating Jersey cows for 20 days with fistula in the rumen during 3 consecutive periods feeding.	The applied method produced quantitative changes in the microbial composition of the rumen. An increase in the amount of SCFA (Short-chain fatty acids), mainly butyrate and valerian, was also observed. The average dry matter (DM) intake for cows fed a corn silage (CS)-based diet was 20.7 kg/day, while cows fed a grass silage (GS)-based diet had an average intake of 17.6 kg/day ($P < 0.05$). The total short-chain fatty acid (SCFA) concentration was significantly higher in cows fed a corn silage (CS)-based diet, with an average of 80.0 ± 2.5 mmol/L, compared to 72.5 ± 2.1 mmol/L in cows fed a grass silage (GS)-based diet ($P < 0.05$). Additionally, butyrate concentrations were 4.7 ± 0.3 mmol/L in the CS group and 3.9 ± 0.2 mmol/L in the GS group, while valerate concentrations were 1.9 ± 0.2 mmol/L in the CS group and 1.5 ± 0.1 mmol/L in the GS group ($P < 0.05$).
Whole maize silage (Guo *et al.* 2022)	Addition of cellulose degrading bacteria to whole maize silage.	The use of cellulose degrading bacteria resulted in an increase in average daily weight gain, feed intake, and the feed conversion ratio of sheep compared to sheep fed feed without cellulose degrading bacteria. It was also observed that cellulose degradation resulted in higher concentrations of volatile fatty acids in rumen samples, lower rumen pH, and higher numbers of *Prevotella* bacteria. Sheep fed whole-plant corn silage treated with bacterial inoculant (WPCSB) showed a significant increase in average daily gain (212.9 g/d vs. 186.0 g/d for WPCS), dry matter intake (1195.6 g/d vs. 1119.6 g/d), and feed conversion rate (0.18 vs. 0.17) compared to those fed untreated corn silage (WPCS). The WPCSB group also exhibited higher concentrations of total volatile fatty acids (62.4 mmol/L vs. 54.5 mmol/L) and propionate (29.0% vs. 22.4%), along with a lower acetate : propionate ratio (2.1 vs. 3.0), while ruminal pH was significantly lower (6.5 vs. 6.7). Moreover, the microbial composition of the WPCSB group showed higher abundance of *Prevotella* and greater activity in pathways related to glycolysis and the citrate cycle, indicating enhanced carbohydrate metabolism.
Corn bran and soybean hulls (Hao *et al.* 2021)	Thirty-six Dorper × Small Thin-Tailed ram lambs were randomized into three groups and each group was fed 1 of 3 compound feeds: 1) 0% corn bran and soybean hulls (sample control); 2) 9% corn bran and 9% soy hulls; 3) 17% corn bran and 17% soy hulls. The feeding experiment	Lambs were more likely to eat feeds with corn bran and soybean hulls (research samples), which resulted in higher average daily gain and feed efficiency compared to the control group. In the research groups, higher digestibility of dry matter and NDF was observed in animals from the research groups. Lambs from group 3 excreted the most purines in their urine, which indicates an increase in protein metabolism in animals with fed with feed containing higher content of corn bran and soybean hulls.

	was conducted for 70 days, the first 10 days of which were devoted to adaptation.	Lambs fed the 34MIX diet (17% corn bran and 17% soybean hulls) had the highest dry matter (60.9%) and aNDF (49.5%) digestibility, along with the greatest ADG (263.6 g/d) and DMI (1635.3 g/d). They also showed higher purine derivatives excretion, particularly allantoin (7.50 mmol/d) and uric acid (1.72 mmol/d), indicating increased protein metabolism. The 34MIX group also had the highest microbial protein yield (53.3 g/d) and daily metabolizable energy intake (1261.4 kJ/kg BW0.75) compared to the control diet group.
Maize germs (Silva *et al.* 2022)	Five sheep were studied during an experimental period consisting of 5 consecutive 22-day periods divided into 14-day adaptation periods and 8-day sampling periods. The diets consisted of maize and cactus silage as roughage and soybean meal, maize meal, EFCG (Extra-fat whole corn germ), urea and mineral premix as a concentrate. The ratio of concentrate to concentrate was 70:30.	The concentration of crude digestible protein compared to bran increased. The rest of the parameters remained unchanged, except for the increased content of cholesterol and triglycerides in the sheep. Crude protein content also showed a significant increase, with values rising from 675.1 g/kg of dry matter at the 0% replacement level to 747.0 g/kg at the 100% replacement level.
Wet Gluten and Corn Straw (Zhang *et al.* 2021)	Nine multiparous Holstein cows were studied over a 21-day period (14 days of diet adaptation and 7 days of sampling). The feeds were fed as TMR mixes containing similar concentrate mixes and maize silage, but different proportions of roughage and WCGF (Wet corn gluten feed). The three types of feeding were as follows: (1) 0% WCGF, 0% maize straw, 22.1% alfalfa hay (0% WCGF); (2) 6.9% WCGF, 3.4% maize straw, 11.8% alfalfa hay (7% WCGF); (3) 13.3% WCGF, 4.9% maize straw, 3.9% alfalfa hay (13.3% WCGF).	Improvement of lactation efficiency and nitrogen utilization in lactating dairy cows. The inclusion of wet corn gluten feed (WCGF) in the diet resulted in significant improvements in milk production and nitrogen utilization. Cows fed with 13.3% WCGF had the highest milk yield (28.6 kg/d), compared to 27.1 kg/d in the 7% WCGF group and 26.3 kg/d in the 0% WCGF group. The energy-corrected milk (ECM) also increased with higher WCGF inclusion, reaching 30.9 kg/d in the 13.3% WCGF group, compared to 29.2 kg/d in the 7% WCGF group and 28.4 kg/d in the control group. Fat and protein yields followed the same trend, with the highest yields observed in the 13.3% WCGF group (1.08 kg/d for fat and 0.89 kg/d for protein). Additionally, milk efficiency improved with higher WCGF inclusion, reaching 1.95 in the 13.3% WCGF group, compared to 1.84 in the 7% WCGF group and 1.71 in the 0% WCGF group. Cows fed 13.3% WCGF had the highest milk nitrogen secretion (140.0 g/d), which represented 28.0% of their nitrogen intake. The fecal nitrogen excretion decreased with higher WCGF, with the lowest excretion observed in the 13.3% WCGF group (174.0 g/d). However, urinary nitrogen excretion increased with WCGF inclusion, with the highest values in the 13.3% WCGF group (127.5 g/d), representing 23.5% of the nitrogen intake. Despite differences in nitrogen excretion, the retained nitrogen did not differ significantly across the treatments, with values around 60-76 g/d. This suggests that WCGF improved nitrogen use efficiency by increasing milk nitrogen secretion while reducing fecal nitrogen excretion.
Gluten and	TMR mixes were prepared with the same mixed	The FTMR (Fermented Total Mixed ration) diet showed good fermentation quality and

maize straw, alfalfa hay (Zhang *et al.* 2020)	ration of concentrate mixes and maize silage, but with different proportions of alfalfa hay, maize straw, and maize gluten. The compositions of the feeds given to each group were as follows: Group 1: 220 g/kg d.m. alfalfa hay. Group 2: 118 g/kg DM alfalfa hay, 68.8 g/kg d.m. of wet maize gluten and 34.4 g/kg s.m. corn straw; Group 3: same composition as Group 2, but the feed was fermented.	improved nutrient digestibility, lactation efficiency, IOFC (Income Over Feed Costs), and nitrogen utilization in dairy cows. The cows fed the FTMR diet had lower DMI (dry mass intake) (17.0 kg/d) and higher milk fat yield (1.14 kg/d) or concentration (39.4 g/kg DM) (P = 0.016, P = 0.021, and P = 0.007, respectively) than cows fed the other two diets, but there was no difference between the TMR A and TMR B diets. The yield of ECM (energy corrected milk) was higher for the cows fed the FTMR diet (31.5 kg/d) than the other two diets (P = 0.0001), but there was no difference between the TMR A and TMR B diets.
Lupine seed (*Lupinus angustifolius*) (Ata and Obeidat 2020)	In the first experiment, 24 Awassi sheep were selected and randomly assigned to one of two diets (12 sheep/diet). Nutrient intake was measured daily during the experiment. Body weight and milk yield were recorded on days 0, 14, 28, and 56. In the second experiment, 12 Awassi lambs were given two diets (6 lambs/diet) to evaluate the effect of LUP supplementation on nutrient digestibility and nitrogen retention balance.	The addition of sweet lupine grain improved the milk characteristics of sheep and the pre-weaning growth of their lambs, as well as nutrient digestibility and N balance. The cost of the diets containing lupine grain was lower. Ewes fed the lupine diet produced more milk (1243 vs. 1096 g/d, P = 0.0371) with higher protein (4.5% vs. 4.2%, P = 0.0042), lactose (6.9% vs. 6.4%, P = 0.0022), and total solids (12.5% vs. 11.7%, P = 0.0063). Their lambs had greater weaning weights (23.9 vs. 20.5 kg, P = 0.0352) and average daily gains (299 *vs*. 244 g/d, P = 0.0105).Lambs on the lupine diet showed improved crude protein (78.0% *vs*. 74.5%, P = 0.0163) and fiber digestibility (65.7% *vs*. 60.5%, P = 0.0134) and retained more nitrogen (59.5% *vs*. 52.4%, P = 0.0484).
Narrow-leaved lupine seed (*Lupinus angustifolius*) (Bryszak *et al.* 2020)	Narrow-leaved lupine seed meal was fed to dairy cows at a dose of 2 kg/day/cow as a component of TMR feed.	The lupine-supplemented diet did not affect milk yield, but it did increase the beneficial fatty acid content; the rumen total volatile fatty acid concentration and acetate content was reduced, as well as the rumen archaea population and methane production. Saturated Fatty Acids (SFA): Significant differences were observed in several saturated fatty acids. For example, the concentration of C12:0 increased from 0.98 g/100 g FA (control) to 1.68 g/100 g FA (at 60 g/kg diet), and C16:0 significantly decreased from 26.1 g/100 g FA (control) to 24.1 g/100 g FA (at 60 g/kg diet). The sum of saturated fatty acids decreased with increasing lupine supplementation, from 77.6 g/100 g FA in the control group to 71.9 g/100 g FA at the 60 g/kg diet. Monounsaturated Fatty Acids (MUFA): The concentration of C18:1 cis-9 (a beneficial fatty acid) increased from 5.38 g/100 g FA in the control to 8.12 g/100 g FA at the highest level of lupine supplementation (100 g/kg diet). The total sum of MUFA increased with lupine supplementation, from 16.4 g/100 g FA in the control to 20.4 g/100 g FA at 60 g/kg diet. Polyunsaturated Fatty Acids (PUFA): The sum of PUFAs also showed a significant increase with lupine supplementation, from 6.02 g/100 g FA in the control to 7.33 g/100 g FA at the 60 g/kg diet. Notably, the n-3 fatty acids, such as C20:5n3 (eicosapentaenoic acid), increased from 0.08 g/100 g FA in the control to 0.14 g/100 g FA at the 100 g/kg diet, contributing to improved beneficial fatty acid content.

The European Union's agricultural policy supports the cultivation of protein crops under the Common Agricultural Policy (CAP), which may improve the profitability of lupine cultivation as an alternative to imported soybean meal (European Commission, 2023). At the same time, many European countries impose restrictions on GMO cultivation, affecting imported soybeans and potentially increasing interest in local protein sources (Erenstein *et al.* 2022).

Fermentation can significantly improve the nutritional value of maize and lupine by increasing protein bioavailability and reducing anti-nutritional factors. To assess the economic feasibility of this approach, a cost-benefit analysis (CBA) should be conducted, considering both costs and benefits. Costs include production expenses such as fertilizers, seeds, plant protection products, harvesting, transportation, and fermentation processes, including the cost of enzymes, energy, and processing infrastructure (Bartkiene *et al.* 2016). The benefits primarily involve improved digestibility and nutritional value, which may lead to better feed efficiency, reduced need for synthetic additives, and decreased dependence on imported soybean meal (Froidmont and Bartiaux-Thill 2004). A break-even analysis should determine whether fermentation costs are offset by increased feed efficiency and potentially higher market value. Additionally, field trials and feeding studies could verify whether fermented maize and lupine-based feeds match or exceed the performance of standard SBM-based mixtures.

In summary, maize and lupine could serve as viable alternatives to soybean meal in Europe, particularly given rising import costs and policies restricting GMO use. Implementing fermentation processes could further enhance their nutritional and economic feasibility, but a comprehensive assessment would require detailed economic analyses and feeding trials.

CONCLUSIONS

Sustainable intensification and precision feeding are essential for addressing the increasing global demand for food while minimizing the environmental impact of ruminant farming. Integrating alternative feed sources such as maize silage and lupine into livestock diets provides a pathway to improving resource efficiency, optimizing nutrient utilization, and reducing methane emissions. These strategies can contribute to a more sustainable food system, by enhancing feed conversion rates and reducing reliance on traditional protein sources which are associated with environmental degradation, such as soybean meal.

The inclusion of maize silage and lupine in ruminant diets has shown potential for mitigating methane emissions. Maize silage can reduce methane emissions by 10 to 20%, due to its high digestibility and efficient fermentation process, while lupine supplementation can lower methane production by an additional 5 to 15%, by modifying rumen fermentation patterns. These reductions are significant in the context of climate change, highlighting the importance of integrating these feed ingredients into conventional livestock feeding strategies to enhance sustainability.

Maize and lupine-based feeds offer a cost-effective alternative to conventional soybean meal, providing economic stability for livestock producers by reducing dependence on imported protein sources. The ability of lupine to fix atmospheric nitrogen also reduces the need for synthetic fertilizers, further reducing production costs. However, economic barriers remain, particularly regarding higher processing costs for lupine and limited commercial production in some regions. Overcoming these challenges will require targeted investment in lupine breeding programs and incentives for farmers to adopt alternative feed sources.

The large-scale adoption of maize and lupine in livestock diets raises regulatory and practical challenges that must be addressed. Lupine's limited use in ruminant diets is partly due to regulatory restrictions on anti-nutritional factors such as alkaloids, necessitating the development of low-alkaloid cultivars that meet safety standards. Additionally, the optimization of fermentation processes through Lactic Acid Bacteria (LAB) inoculants is critical for enhancing feed efficiency and maximizing methane reduction benefits. Policies supporting research and implementation of these techniques will be essential to promote their widespread adoption.

Further research is needed to optimize maize-lupine diets for large-scale livestock production. Developing low-alkaloid lupine cultivars will improve digestibility and reduce potential negative effects on animal health. Long-term studies should assess the impact of these feed sources on milk yield, meat quality, and overall animal productivity, ensuring their economic and nutritional viability. Additionally, economic and environmental modeling should be conducted to evaluate the long-term cost-benefit ratio of maize and lupine integration compared to conventional feeds. By addressing these research gaps, it will be possible to enhance livestock sustainability while reducing the environmental footprint of ruminant farming.

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