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Optimizing Goat Feed Formulation to Reduce Costs and Improve Production Efficiency

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Abstract This study evaluated the specific nutritional needs of goats at different stages of their life, including energy, protein, vitamins, and minerals. It emphasized the potential uses of by-products and alternative sources, explored sustainable feed practices, with a focus on locally sourced raw materials and reducing environmental impact, and used a commercial goat farm as a case study to implement and evaluate proposed strategies. The study emphasized the importance of integrating advanced feed formulation tools and sustainable practices in goat farming, and clarified that future research should explore the application of nutrigenomics, innovative feed additives, and artificial intelligence to further improve feed optimization and industry sustainability. This study aims to develop and evaluate optimized feed formulation strategies that balance nutritional adequacy and economic feasibility.
Keywords Goat farming; Feed formulation; Cost-effectiveness; Precision nutrition; Alternative feed sources

1 Introduction

Goat farming is a significant agricultural activity that contributes to the socio-economic development of many regions worldwide. It provides essential products such as milk, meat, and fiber, which are crucial for the livelihoods of many rural communities. In regions like Northern Mexico and Greece, goat farming is particularly vital due to its adaptability to arid and semi-arid conditions, making it a resilient agricultural practice in the face of climate change (Machado-Ramos et al., 2023). The economic importance of goat farming is underscored by its ability to utilize low productivity pastures and shrublands, thereby converting otherwise unproductive land into valuable agricultural output (Sintori et al., 2019).

Despite its economic significance, goat farming faces several challenges that hinder its productivity and profitability. Key among these challenges is the high cost of feed, which constitutes a major portion of the production expenses. The quality and formulation of feed are critical factors that influence the productivity of goats, including their milk yield and reproductive performance (Moroz and Samorukov, 2020; Rodrigues et al., 2021). Inadequate or imbalanced nutrition can lead to suboptimal growth, poor health, and reduced reproductive efficiency. Moreover, the environmental impact of goat farming, particularly greenhouse gas emissions, is a growing concern that necessitates the adoption of sustainable feeding practices. Optimizing feed formulation not only aims to reduce costs but also to enhance production efficiency and sustainability by incorporating alternative feed sources and improving nutrient balance (Saputro et al., 2023).

This study identified cost-effective and sustainable feed choices to improve the economic feasibility of goat farming by studying various feeding strategies and their impact on productivity. The use of alternative feed sources such as palm kernel cake and cow feed residue was evaluated, as well as their effects on growth, milk production, and reproductive performance. The potential for reducing greenhouse gas emissions through improved feed practices was analyzed, providing practical recommendations for goat farmers to explore and optimize goat feed formulations to reduce production costs and improve overall production efficiency.

2 Nutritional Requirements of Goats

2.1 Energy and protein needs across different stages (kids, lactating does, mature goats)

Goats have varying energy and protein requirements depending on their life stage. For instance, growing goat kids require adequate protein to support their rapid growth and development. A study on Anhui white goat kids demonstrated that a diet containing 13.4% crude protein (CP) was sufficient to improve nitrogen utilization without adversely affecting growth performance, suggesting that this level of protein is optimal for young goats. Lactating does, on the other hand, have increased energy and protein needs to support milk production. Research has shown that replacing a portion of the concentrate feed with Moringa oleifera silage and Chlorella vulgaris microalgae can enhance milk production and nutrient utilization in lactating goats, indicating the importance of high-quality protein sources during lactation (Kholif et al., 2022).

Mature goats, particularly those in maintenance or non-reproductive phases, have lower energy and protein requirements compared to growing kids and lactating does. However, strategic nutrient supplementation, such as the inclusion of clay minerals like bentonite, can still positively impact nutrient digestibility and overall health (Helmy et al., 2022).

2.2 Role of essential vitamins and minerals

Vitamins and minerals play crucial roles in the health and productivity of goats. Essential minerals such as calcium, phosphorus, and magnesium are vital for bone development, metabolic processes, and overall health. For instance, the inclusion of vitamin-mineral mixtures in feed blocks has been shown to support nutrient utilization and milk composition in goats (Molina-Alcaide et al., 2010).

Vitamins, particularly vitamin A, are essential for vision, immune function, and reproduction. Supplementation with plant extracts and yeast cell wall components, which are rich in vitamins and minerals, has been found to enhance rumen development and overall health in young goats (Belanche et al., 2023).

2.3 Impact of nutritional deficiency on health and productivity

Nutritional deficiencies can have severe impacts on the health and productivity of goats. For example, a deficiency in dietary protein can lead to reduced growth rates, poor feed efficiency, and increased nitrogen excretion, as observed in studies on low-protein diets in goat kids (Zhu et al., 2020).

Similarly, deficiencies in essential vitamins and minerals can lead to various health issues. For instance, inadequate mineral supplementation can result in poor bone development, metabolic disorders, and decreased reproductive performance. Research has shown that goats consuming low-quality forages with high fiber and low protein content benefit significantly from protein and mineral supplementation, which improves intake and performance (Kawas et al., 2010).

3 Feed Ingredients and Their Cost-Effectiveness

3.1 Common feed ingredients in goat diets (grains, forages, supplements)

Goat diets typically include a variety of grains, forages, and supplements to meet their nutritional needs (Figure 1). Common grains used are corn, barley, and wheat, which provide essential carbohydrates and energy (Liu and He, 2024). Forages such as alfalfa hay are crucial for fiber intake and overall digestive health. Supplements, including soybean meal and vitamin-mineral mixtures, are often added to ensure goats receive adequate protein and micronutrients (Molina-Alcaide et al., 2010; Pentz and Jones, 2019).

3.2 Evaluating the cost and availability of feed ingredients

The cost and availability of feed ingredients can vary significantly based on regional factors and market conditions. For instance, barley has been identified as a cost-effective grain that can replace more expensive grains like wheat and corn under certain price conditions, leading to potential cost savings in feed formulation (Alqaisi et al., 2019). Additionally, the use of local by-products such as olive and tomato silages can enhance farm profitability by reducing reliance on imported conventional ingredients (Arco-Pérez et al., 2017). The fluctuating

prices of feed ingredients necessitate dynamic feed formulation models to optimize costs while maintaining nutritional adequacy.

Figure 1 Goats fed with feed

3.3 Use of by-products and alternative feed sources to reduce costs

Incorporating by-products and alternative feed sources into goat diets can significantly reduce feeding costs without compromising production efficiency. By-products such as brewer's grain, citrus pulp, and tomato fruits have been successfully used to replace conventional ingredients in goat diets, resulting in lower feed costs and improved nutrient utilization (Romero-Huelva et al., 2017). Similarly, the inclusion of cocoa bean shell in goat diets has shown promise in reducing diet costs while maintaining milk production performance (Renna et al., 2022). Furthermore, using feed leftovers from dairy cows as a supplement for goats has been demonstrated to enhance reproductive performance and reduce feed waste, promoting a circular economy approach (Machado-Ramos et al., 2023). These strategies not only lower feed costs but also contribute to environmental sustainability by reducing food-feed competition and waste (Lee et al., 2014; Ertl et al., 2015; Karlsson et al., 2018).

4 Feed Formulation Strategies

4.1 Balancing nutritional needs with economic viability

Balancing the nutritional needs of goats with economic viability is a critical aspect of feed formulation. The goal is to provide adequate nutrients to support optimal growth, reproduction, and health while minimizing costs. One effective strategy is the use of precision feeding, which tailors diets to the specific needs of individual animals or groups, thereby improving nutrient utilization and reducing waste (Șonea et al., 2023). For instance, reducing crude protein content in diets and supplementing with synthetic amino acids can enhance nitrogen efficiency and

lower feed costs (Pomar et al., 2021). Additionally, integrating local feedstuffs and non-human-edible products can further reduce the carbon footprint and feed expenses.

4.2 Software tools and models for optimal feed formulation

The use of advanced software tools and models is essential for optimizing feed formulation. These tools can handle complex variables such as fluctuating feed prices, nutrient compositions, and animal requirements. For example, evolutionary multi-objective optimization algorithms like NSGA-II can minimize feed costs while meeting nutritional requirements, providing a set of optimal solutions for decision-makers (Uyeh et al., 2019). Similarly, precision nutrition models, such as the Agricultural Modeling and Training Systems (AMTS) CattlePro, can simulate the effects of different diet formulation frequencies on dairy cattle performance, demonstrating significant economic benefits from more frequent diet adjustments (White and Capper, 2014). These tools facilitate efficient decision-making and can significantly enhance the economic viability of feed formulation strategies.

4.3 Role of precision nutrition in reducing feed wastage

Precision nutrition plays a pivotal role in reducing feed wastage and improving overall feed efficiency. By customizing diets to the specific needs of individual animals, precision feeding ensures that nutrients are utilized more effectively, thereby minimizing waste (Gaillard et al., 2020). For instance, precision feeding can reduce lysine intake and nitrogen excretion in pigs without compromising their performance, leading to lower feeding costs and environmental impact (Andretta et al., 2016). Additionally, precision supplementation in heifer development programs can optimize individual animal intake, reduce feed overconsumption, and improve uniformity in growth and reproductive performance (Dagel et al., 2022). These strategies not only enhance feed efficiency but also contribute to the sustainability of livestock production systems.

5 Impact of Feed Quality on Goat Productivity

5.1 Influence of feed quality on milk yield and meat production

Feed quality significantly influences both milk yield and meat production in goats. High-quality feed formulations, such as those incorporating Moringa oleifera silage and Chlorella vulgaris microalgae, have been shown to improve milk production and composition. Specifically, replacing up to 40% of the concentrate mixture with these components increased daily milk production, milk fat, and lactose concentrations, as well as feed efficiency in Damascus goats (Table 1) (Kholif et al., 2022). Similarly, the inclusion of mango seeds as an alternative energy source in the diet of dairy goats resulted in higher milk yield and improved milk composition, including increased total solids, protein, and fat content (El-Sanafawy et al., 2023). For meat production, the use of Ginkgo biloba residues to partially replace alfalfa hay pellets in the diet of finishing goats improved growth performance and meat quality, demonstrating the potential of high-quality feed to enhance both milk and meat productivity.

5.2 Improving digestibility and feed conversion efficiency

Improving the digestibility and feed conversion efficiency of goat diets is crucial for optimizing production. Studies have shown that the inclusion of yeast-fermented palm kernel cake protein in place of soybean meal can enhance the digestibility of dry matter, crude protein, and fiber, thereby improving overall feed utilization efficiency (Chanjula et al., 2022). Additionally, the use of agro-industrial by-products like yeast- or EM-fermented cassava peel has been found to maintain feed intake and digestibility while significantly reducing feed costs, thus enhancing feed conversion efficiency (Gunun et al., 2023). Furthermore, the supplementation of diets with bee bread extract has been shown to improve the digestibility coefficients and nutritive value, leading to better feed conversion and daily weight gain in suckling kids (Farag et al., 2021).

5.3 Addressing feed safety concerns (contaminants, mycotoxins)

Ensuring feed safety is paramount to maintaining goat health and productivity. Contaminants and mycotoxins in feed can have detrimental effects on animal health and performance. The use of slow-release urea as a partial replacement for soybean meal has been shown to improve feed efficiency and reduce the environmental footprint without compromising animal health, indicating a safer alternative to traditional protein sources (Grossi et al.,

2021). Additionally, the inclusion of natural plant extracts and yeast cell wall components in early life diets can optimize rumen development and reduce the incidence of health issues, thereby promoting safer and more efficient feed utilization (Belanche et al., 2023). These strategies highlight the importance of addressing feed safety concerns to ensure the well-being and productivity of goats.

Table 1 Milk yield and composition in lactating Damascus goats fed diets containing *Moringa oleifera* and *Chlorella vulgaris microalgae* (n = 15) (Adopted from Kholif et al., 2022)

	Diet 1				*p* Values	
	Control	MA20	MA40	SEM	Diet	Control vs. Others
Production, g/d (unless stated otherwise)						
Milk	876 [b]	1003 [a]	1023 [a]	32.0	0.005	0.001
Energy corrected milk (ECM)	839 [b]	1066 [a]	1030 [a]	33.3	<0.001	<0.001
Fat corrected milk (4% FCM)	828 [b]	1026 [a]	998 [a]	32.0	0.001	<0.001
Milk energy output, MJ/d	2.58 [b]	3.29 [a]	3.18 [a]	0.103	<0.001	<0.001
Total solids	108 [b]	137 [a]	132 [a]	4.3	<0.001	<0.001
Solids non-fat	76.3 [b]	95.4 [a]	92.0 [a]	3.07	0.002	<0.001
Fat	31.8 [b]	41.1 [a]	39.8 [a]	1.29	<0.001	<0.001
Protein	32.9 [b]	40.7 [a]	39.7 [a]	1.41	0.006	0.002
Lactose	36.2 [b]	46.2 [a]	44.0 [a]	1.40	<0.001	<0.001
Composition, g/kg unless stated otherwise						
Total solids	123	133	131	3.96	0.062	0.066
Solids non-fat	87.0	93.3	91.8	3.97	0.055	0.072
Fat	36.3 [b]	40.2 [a]	39.7 [a]	0.37	<0.001	<0.001
Protein	37.6	39.8	39.5	2.52	0.091	0.205
Lactose	41.3 [b]	45.2 [a]	43.9 [a]	0.58	0.001	<0.001
Milk energy content, MJ/kg	2.94 [b]	3.22 [a]	3.17 [a]	0.022	<0.001	<0.001
Feed efficiency						
Milk: intake ratio	0.74 [b]	0.87 [a]	0.86 [a]	0.028	0.004	0.009
ECM: intake ratio	0.71 [b]	0.91 [a]	0.89 [a]	0.030	<0.001	<0.001
FCM: intake ratio	0.70 [b]	0.88 [a]	0.86 [a]	0.028	<0.001	<0.001

Note: [a,b] Means in the same row with different superscripts differ at $p < 0.05$. p-value is the observed significance level of the F-test for treatment; SEM, standard error of the mean. [1] Diets: Concentrate mixture in the control diet was replaced with *Chlorella vulgaris microalgae* (at 1%) and *Moringa oleifera* silage at 0% (Control diet), 20% (MA20 diet) or 40% (MA40 diet), DM basis (Adopted from Kholif et al., 2022)

6 Case Study

6.1 Background and overview of the selected goat farm/region

The selected goat farm is located in the North-West District of Russia, focusing on the Saanen breed, known for its high milk production potential. This region experiences a temperate climate, which influences the feeding strategies and overall management practices. The farm has been operational for over a decade and has recently adopted advanced feed formulation techniques to enhance productivity and reduce costs (Moroz and Samorukov, 2020).

6.2 Implemented feed formulation strategies and changes made

The farm implemented several feed formulation strategies to optimize the nutrition of their dairy goats. One of the primary changes was the introduction of the "RATIONS" information and analytical system to calculate balanced rations tailored to the nutrient requirements of the Saanen goats. This system allowed for precise adjustments in feeding rates, ensuring that the goats received adequate nutrition to maximize milk production. Additionally, the farm incorporated feed leftovers from nearby dairy cow farms, following a circular economy approach to reduce

waste and improve feed efficiency (Figure 2) (Machado-Ramos et al., 2023). This strategy not only provided a cost-effective feed source but also enhanced the reproductive performance of the goats during the off-season.

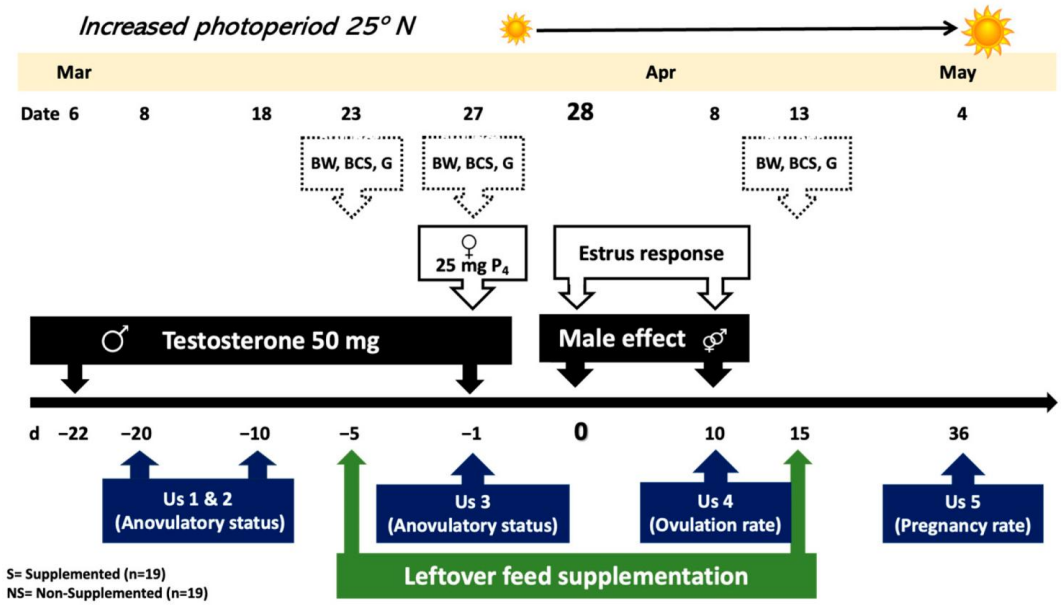

Figure 2 Schematic representation of the experimental protocol in of multiparous crossbred/rangeland goats (n = 38) (i.e., extensive system) receiving (S) or not (NS) a nutritional supplementation of feed leftovers from a dairy cow enterprise (i.e., intensive system) in Northern Mexico (Adopted from Machado-Ramos et al., 2023)

6.3 Outcomes and benefits observed (cost reduction, increased productivity)

The implementation of these feed formulation strategies led to significant outcomes and benefits for the farm. Firstly, there was a noticeable reduction in feed costs due to the utilization of dairy cow feed leftovers and the precise calculation of balanced rations. The farm observed a 7.4% increase in milk productivity, attributed to the improved nutritional intake of the goats. Additionally, the reproductive performance of the goats improved, with higher ovulation and pregnancy rates observed during the off-season, which was a direct result of the targeted supplementation strategy. Overall, these changes contributed to a more efficient and cost-effective production system.

6.4 Lessons learned and implications for broader application

Several key lessons were learned from this case study. Firstly, the importance of precise feed formulation cannot be overstated. Utilizing advanced systems like "RATIONS" can significantly enhance the nutritional intake of goats, leading to increased productivity and reduced costs. Secondly, adopting a circular economy approach by using feed leftovers from other livestock farms can provide a sustainable and cost-effective feed source, improving overall farm efficiency. Lastly, the integration of modern technologies and data-driven decision-making tools, such as the Eskardillo system, can further optimize farm management and contribute to sustainable intensification (Belanche et al., 2019).

The implications for broader application are clear. Farms in similar regions or with similar breeds can adopt these strategies to improve their production efficiency and reduce costs. The use of advanced feed formulation systems and the incorporation of feed leftovers can be particularly beneficial in regions with limited feed resources or high feed costs. Additionally, the integration of data-driven tools can help farmers make informed decisions, leading to better management practices and improved productivity.

7 Sustainability in Goat Feed Formulation

7.1 Incorporating locally sourced ingredients

Incorporating locally sourced ingredients into goat feed formulations can significantly enhance sustainability by reducing transportation-related greenhouse gas emissions and supporting local economies. For instance, the use of

local agricultural by-products, such as artichoke by-product silage (ABS), has been shown to reduce production costs and improve environmental sustainability without significantly affecting milk yield and quality in dairy goats (Monllor et al., 2021). Similarly, the inclusion of cocoa bean shell (CBS), a by-product of the cocoa industry, in goat diets has demonstrated potential as a sustainable feed ingredient, maintaining milk production performance while altering the fatty acid profile beneficially (Renna et al., 2022). Utilizing local protein sources and by-products not only minimizes the carbon footprint associated with feed transportation but also promotes the efficient use of regional resources (Dierenfeld, 2023).

7.2 Reducing the environmental impact of feed production

Reducing the environmental impact of feed production is crucial for sustainable livestock farming. Innovative feed formulation methodologies, such as multi-objective (MO) formulations, can balance cost and environmental impacts, leading to reduced greenhouse gas emissions, non-renewable energy demand, and phosphorus demand (Quelen et al., 2021). Additionally, the use of highly digestible protein feed materials can improve nitrogen-use efficiency, thereby reducing nitrogen losses to the environment and decreasing ammonia emissions (Chojnacka et al., 2021). Strategies like replacing soybean meal with slow-release urea sources have also been effective in reducing the carbon footprint and methane emissions in dairy cows, which can be adapted for goat feed formulations (Grossi et al., 2021). These approaches highlight the importance of integrating environmental considerations into feed formulation processes to achieve sustainable livestock production.

7.3 Strategies for sustainable feed formulation practices

Several strategies can be employed to develop sustainable feed formulation practices for goats. One effective approach is the use of precision feeding and nutrition, which tailors diets to the specific nutrient requirements of animals, thereby maximizing nutrient efficiency and minimizing waste (Pomar et al., 2021). This method can significantly reduce nitrogen excretion and improve the overall sustainability of livestock production. Another strategy involves the use of life cycle assessment (LCA) to evaluate the environmental impacts of different feed ingredients and formulations, enabling the selection of ingredients with lower environmental footprints (Heidari et al., 2021). Additionally, incorporating regenerative agriculture practices and bio-circularity, such as using residues, by-products, and excess food streams, can enhance the sustainability of feed systems by reducing greenhouse gas emissions and promoting resource efficiency. These strategies collectively contribute to the development of sustainable feed formulations that support both environmental and economic goals in goat farming.

8 Future Directions in Goat Feed Formulation

8.1 Advances in nutrigenomics and precision feeding

Nutrigenomics, the study of how nutrition affects gene expression, is emerging as a pivotal tool in optimizing feed formulation for goats. By understanding the molecular mechanisms through which nutrients influence gene expression, it is possible to tailor diets that enhance growth, health, and productivity. This approach has shown promise in improving the performance and health of animals selected for further production, although the molecular mechanisms are not yet fully understood (Hashemi et al., 2020). Precision feeding, which involves providing individualized diets based on the specific needs of each animal, has also demonstrated significant potential. For instance, algorithms designed for precision feeding in dairy cattle have been shown to improve feed efficiency and reduce costs, suggesting similar benefits could be achieved in goat farming (Dagel et al., 2022; Souza et al., 2022). These advancements could lead to more efficient nutrient utilization, better health outcomes, and increased profitability in goat production.

8.2 Innovations in alternative protein sources and feed supplements

The search for alternative protein sources and feed supplements is crucial for reducing feed costs and improving sustainability in goat farming. Studies have shown that replacing traditional concentrate feeds with alternatives like *Moringa oleifera silage* and *Chlorella vulgaris microalgae* can enhance nutrient digestibility, ruminal fermentation, and milk production in goats (Kholif et al., 2022). Additionally, the use of feed leftovers from dairy cows as a supplement for goats has been explored as a circular economy approach, improving reproductive

performance and benefiting marginal producers (Machado-Ramos et al., 2023). Early life supplementation with natural blends containing turmeric, thymol, and yeast cell wall components has also been found to optimize rumen development and increase body weight gain in young goats, although the long-term productive implications are minor (Belanche et al., 2023). These innovations not only reduce reliance on high-cost feed ingredients but also promote sustainable farming practices.

8.3 Potential of AI and machine learning in optimizing feed formulation

Artificial intelligence (AI) and machine learning (ML) are poised to revolutionize feed formulation by enabling more precise and efficient feeding strategies. AI-driven algorithms can analyze vast amounts of data to optimize feed composition and delivery, ensuring that each goat receives the right nutrients at the right time. For example, precision feeding systems for pigs and dairy cattle have shown that AI can significantly improve feed efficiency and reduce nutrient waste (Gaillard et al., 2020; Pomar et al., 2021). These technologies can be adapted for goat farming to enhance feed efficiency, reduce costs, and improve overall production efficiency. The integration of AI and ML in feed formulation represents a significant step forward in achieving sustainable and profitable goat farming.

9 Concluding Remarks

The optimization of goat feed formulation has been extensively studied with the aim of reducing costs and improving production efficiency. Several methods have been proposed, including the use of linear programming to design optimal feed formulations that minimize costs while meeting nutritional requirements. The incorporation of agro-industrial by-products, such as yeast- or EM-fermented cassava peel, has been shown to replace up to 50% of concentrate without negatively impacting feed intake, digestibility, or growth performance, thereby reducing feed costs by up to 32%. Similarly, the inclusion of tomato pomace in goat diets has been found to improve milk production and quality without adverse effects on animal health, with a 40% inclusion level being optimal. Additionally, the use of yeast-fermented palm kernel cake as a substitute for soybean meal has demonstrated potential in maintaining feed efficiency and reducing costs. Advanced mathematical models, such as multi-objective optimization algorithms, have also been developed to balance cost and nutritional requirements more effectively.

Goat farmers and feed producers are encouraged to adopt several strategies to optimize feed formulation. Firstly, utilizing linear programming tools can help in designing cost-effective feed formulations that meet the nutritional needs of goats. Incorporating agro-industrial by-products like cassava peel and tomato pomace can significantly reduce feed costs while maintaining or even enhancing production efficiency. It is also recommended to explore the use of yeast-fermented alternatives to traditional protein sources, such as palm kernel cake, to further reduce costs without compromising feed quality. Additionally, adopting a circular economy approach by using feed leftovers from other livestock systems can improve reproductive performance and overall efficiency. Finally, employing advanced optimization algorithms can provide a comprehensive set of solutions that balance cost and nutritional requirements, facilitating better decision-making.

The future of goat feed optimization lies in the integration of advanced technologies and sustainable practices. The use of linear programming and multi-objective optimization algorithms will continue to play a crucial role in developing cost-effective and nutritionally balanced feed formulations. The incorporation of agro-industrial by-products and the adoption of circular economy principles will not only reduce feed costs but also promote environmental sustainability. As research progresses, the development of more precise and adaptable feed formulations will be essential to meet the evolving needs of goat production systems. By embracing these innovations, the goat farming industry can achieve greater efficiency, profitability, and sustainability in the long term.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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