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Development of Precision Feed Technology Model for Ruminant Livestock Based on Nutritional Sensors

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ABSTRACT

Feeding is a key factor in ruminant livestock production systems, often ignoring the variations in individual nutritional needs of livestock, reducing efficiency and increasing feed waste. Therefore, this study aims to examine and develop a precision feeding technology model concept for ruminant livestock based on nutritional sensors through a descriptive-interpretive approach based on the latest scientific literature. The results show that the use of nutritional sensors, rumen sensors, feed consumption sensors, and feeding behavior sensors allows for real-time monitoring of livestock physiological conditions and nutritional status. Integration of sensor data into an adaptive nutrition model has been shown to improve the accuracy of estimating individual nutritional requirements, reduce the risk of overfeeding and underfeeding, and increase feed efficiency. Further discussion shows that although precision feeding technology has developed rapidly, its application is still dominated by intensive livestock systems in developed countries.

Keywords:, ***Precision Feeding; Ruminant Livestock; Nutritional Sensors; Precision Feeding Model; Livestock Technology***

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INTRODUCTION

Ruminant livestock systems have become a major concern in relation to global food security. The increasing demand for animal-based food, pressure on natural resources, and the need to reduce greenhouse gas emissions have raised serious questions about the sustainability of conventional livestock production systems. One of the most critical aspects of ruminant production is feed management, as feed accounts for more than 60–70% of total production costs and directly affects productivity and environmental impacts (Tedeschi et al., 2019). Precision feeding has therefore emerged as an innovative approach aimed at matching nutrient supply more accurately and dynamically with the actual requirements of individual animals.

Precision feeding is positioned as an integral component of the precision livestock farming (PLF) paradigm, which utilizes sensors, big data, and modeling to optimize individual animal management (González et al., 2018). Conventional feeding systems often result in nutrient oversupply or deficiency, leading to poor feed conversion efficiency and increased nitrogen excretion and enteric methane emissions (Liebe & White, 2019). The FAO emphasizes that improving nutrient-use efficiency is one of the most effective strategies for reducing the carbon footprint of the livestock sector without lowering production levels (Empel et al., 2016).

National ruminant production systems are dominated by small- and medium-scale farms that rely heavily on local forages whose quality and availability fluctuate considerably. Feed formulation is generally based on average nutritional requirements, without accounting for individual variation or temporal changes in physiological and environmental conditions. This situation contributes to low productivity, high feed costs, and inefficient resource use (Tedeschi et al., 2019).

Limited adoption of nutritional monitoring technologies at the farm level means that feeding decisions remain reactive and based largely on subjective experience. However, numerous studies demonstrate that nutritional sensors such as rumen pH sensors, feeding behavior sensors, and near-infrared spectroscopy (NIRS) for forage quality analysis can provide real-time data on animal nutritional status and responses to feed (Knight, 2020; Caja et al., 2020). Thus, in this research, precision feeding is viewed not merely as a technological innovation but as a strategic issue in livestock development that directly affects farmer welfare and food security.

Nutritional problems in ruminant livestock also have strong socio-economic dimensions. Inappropriate feeding leads to poor animal performance, increased risk of metabolic disorders, and feed wastage that ultimately causes economic losses for farmers. Moreover, excessive nutrient excretion can pollute the surrounding environment, especially in smallholder systems integrated with residential areas (Loučka et al., 2023). Therefore, research on the development of sensor-based precision feeding models clearly addresses real social problems, rather than being limited to purely academic concerns.

Uniform "one-size-fits-all" feeding practices are no longer relevant, as they ignore individual differences in physiological status, production level, health, and metabolic response to feed (Kyriazakis, 2023). Most precision feeding models have been developed for intensive livestock systems in subtropical regions with relatively homogeneous feed quality and standardized management. This context differs markedly from tropical ruminant systems, which are characterized by high forage variability, extreme seasonal fluctuations, and limited technological inputs (Tedeschi et al., 2019; Webster, 2025).

Using a literature-based approach, this paper synthesizes findings from relevant previous studies. The main focus is on precision feeding technology models, their technical mechanisms, and their application in ruminant nutrition management. The research questions addressed are: (1) what are the characteristics of current ruminant feeding systems prior to the adoption of sensor-based precision feeding technologies; (2) how do nutritional sensors work in identifying and monitoring the nutritional requirements of ruminants; and (3) what is the potential of sensor-based precision feeding models to improve the efficiency of ruminant feeding systems.

METHODS

This study employed a literature review method using a qualitative–interpretative approach. This approach was selected because the objective was to systematically, factually, and accurately describe the characteristics, components, and working mechanisms of sensor-based precision feeding technology models in ruminant livestock. A descriptive orientation was adopted since the study does not focus on hypothesis testing or causal relationships, but rather on portraying real conditions, explaining processes, and identifying the defining features of technological models that have been developed and implemented in practice.

Data sources for this study were obtained from various scientific literatures, including national and international journals, academic books, research reports, and relevant documents addressing the main topics of interest. Sources were selected purposively based on content relevance, author credibility, and the novelty of the information, ensuring that the review provides a deep and contextualized synthesis of existing knowledge.

Data analysis involved several stages: organizing the extracted information, categorizing findings from the reviewed sources, synthesizing the results, and drawing research conclusions based on the integrated evidence (Sahir, 2022).

RESULTS AND DISCUSSION

Concept and Evolution of Precision Feeding in Ruminant Production Systems

Precision feeding is an integral part of the Precision Livestock Farming (PLF) approach, which aims to optimize feed-use efficiency, enhance animal productivity, and minimize environmental impacts by supplying nutrients dynamically according to the individual requirements of animals (González et al., 2018). In ruminant systems, this approach is increasingly relevant due to the complexity of digestion, variability in feed intake, and the interactions among nutrients, rumen microbes, and animal physiological conditions (Tedeschi et al., 2019).

Ruminant feeding systems are still largely dominated by ration-based feeding approaches, where feed formulation is based on the average requirements of animal groups. This method is poorly adaptive to individual variation and field dynamics, leading to feed inefficiencies and nutrient wastage (Cannas et al., 2019). Precision feeding addresses this limitation by integrating nutritional models, biological sensors, and data-driven decision-making systems.

The evolution of nutritional modeling has shifted from static models toward hybrid models that integrate biological principles with sensor-based data analytics and artificial intelligence. Menendez et al. (2022) reported that incorporating sensor data into ruminant nutrition models improves the prediction of animal responses to dietary changes. Decision Support Systems (DSS) and digital twin technologies are increasingly applied in ruminant precision feeding. Rao and Neethirajan (2024) demonstrated that sensor-based digital twin models can simulate individual nutritional responses and provide more accurate feeding recommendations. However, most studies remain at experimental scales and have not been widely implemented in smallholder or semi-intensive systems, particularly in tropical regions (Makinde, 2020; Pomar & Remus, 2023).

Evidence shows that sensor-based precision feeding positively affects production efficiency and environmental sustainability. Tedeschi et al. (2021) reported that precise protein supply can reduce nitrogen excretion by 20–30% without compromising production performance. Similarly, González et al. (2023) observed reductions in enteric methane emissions through energy supply adjustments guided by sensor data. Precision feeding also improves economic efficiency. Amirault et al. (2022) showed that the use of nutritional sensors and precision feeding systems reduced feed costs by 10–15% in intensive dairy operations. Nevertheless, adoption is constrained by high investment costs, system complexity, and limited user capacity (Moreira et al., 2024).

Nutrition as the Foundation of Precision Feeding Technology

Advances in sensor technologies have been the main catalyst for the implementation of precision feeding. Nutritional sensors in ruminant livestock include rumen bolus sensors, feeding activity sensors, ingestive behavior sensors, near-infrared spectroscopy (NIRS) for forage quality analysis, and physiological sensors such as rumen pH, body temperature, and heart rate (Amirault, 2023; Roqueto dos Reis, 2023).

Empel et al. (2016) emphasized that an ideal precision feeding system must combine real-time sensors with predictive models capable of estimating animal responses to nutritional changes. Previous studies show that integrating sensor data with mathematical modeling improves the accuracy of nutrient requirement estimates compared with conventional methods (Menendez et al., 2022). Pomar and Remus (2023) cautioned that many precision feeding systems still focus mainly on sensor technology without full integration with ruminant biological models, limiting their optimization potential.

Recent studies indicate that sensor-based precision feeding improves the accuracy of individual nutrient requirement estimation. Condotta et al. (2021) demonstrated that using feed intake and daily body weight sensor data reduced energy requirement estimation errors by 15–25% compared with group-average approaches. Other research has shown that inter-individual variation in protein and energy requirements within the same herd is substantial and cannot be accommodated by conventional feeding systems (Sonea et al., 2023). By using nutritional sensors and adaptive models, precision feeding allows dynamic adjustment of nutrient supply in response to physiological changes such as lactation stage, growth, or environmental stress (Zhang et al., 2025).

Nutritional Models and Theoretical Approaches in Precision Feeding

Ruminant nutrition models form the backbone of precision feeding development. Mechanistic models such as CNCPS, NRC, and rumen dynamic models are used to predict nutrient flows, microbial production, and the efficiency of energy and protein metabolism (Tedeschi et al., 2019; Cannas et al., 2019). Hybrid modeling approaches that combine mechanistic models with machine learning and artificial intelligence are increasingly used to process large-scale sensor data (Zhang et al., 2025). Liebe and White (2019) emphasized that integrating sensor data into nutrition models enables precision feeding systems to function as adaptive and predictive decision support systems.

Digital twin approaches are also being applied in ruminant nutrition, where virtual representations of animals are used to simulate nutritional responses based on real-time sensor data (Rao & Neethirajan, 2025). This theoretical perspective helps explain how complex interactions among nutrition, physiology, and environment can be dynamically modeled.

Practical benefits of sensor-based precision feeding are evident. Ojo et al. (2024) reported improved feed efficiency and reduced performance variability in beef cattle through sensor-based monitoring of feeding behavior. Dagel (2023) showed that precision supplementation systems in heifers reduced feed costs without compromising growth performance. González et al. (2023) demonstrated that sensors and nutrition models enable individualized feed management in grazing ruminants, although environmental challenges remain significant. Fernandes and Tedeschi (2025) highlighted the potential integration of sensor data with remote sensing to support precision feeding in sustainable pasture-based systems.

Overall, sensor-based precision feeding enhances the accuracy of estimating individual nutrient requirements in ruminant livestock. Condotta et al. (2021) confirmed that using feed intake and daily body weight sensor data reduces energy requirement estimation errors by 15–25% compared with group-based approaches. Given the substantial inter-individual variation in protein and energy needs (Sonea et al., 2023), precision feeding supported by nutritional sensors and adaptive models enables dynamic nutrient supply adjustments aligned with physiological stages and environmental conditions (Zhang et al., 2025).

CONCLUSION AND IMPLICATIONS

The findings of this study confirm that the development of sensor-based precision feeding technology models has both strong scientific relevance and high practical significance. These models have the potential to serve as a cornerstone in transforming ruminant feed management systems from conventional, experience-based practices into more efficient, sustainable, and data-driven systems. By integrating real-time nutritional sensors with adaptive nutritional models, precision feeding enables a more accurate alignment between nutrient supply and the actual physiological needs of individual animals, which is essential for improving productivity and resource-use efficiency in modern livestock production.

From an environmental perspective, adaptive precision feeding models can substantially reduce feed wastage, lower excess nutrient excretion, and mitigate the environmental footprint of ruminant production, particularly in terms of nitrogen losses and enteric methane emissions. These outcomes support broader goals of sustainable agriculture and climate-smart livestock development. At the same time, precision feeding contributes to animal welfare by minimizing metabolic stress associated with underfeeding or overfeeding and by promoting more stable physiological conditions throughout different production stages.

Nevertheless, the review also highlights a significant gap between technological development and field-level implementation. Most precision feeding innovations have been designed and tested within intensive livestock systems in developed countries, where infrastructure, data availability, and technological capacity are relatively high. In contrast, ruminant production systems in many developing and tropical regions characterized by smallholder farms, variable forage resources, and limited access to digital technologies require more context-specific, affordable, and user-friendly precision feeding models.

Therefore, future research and development should focus on simplifying sensor systems, integrating locally available feed resources into adaptive nutrition models, and strengthening farmer capacity through training and institutional support. By doing so, sensor-based precision feeding can be more widely adopted and become a realistic pathway for improving national ruminant production systems, enhancing farmer livelihoods, and ensuring long-term food security and environmental sustainability.

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