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Review Article

Enhancing Nitrogen Utilization in Dairy Cattle by Precision Protein Feeding: A Systematic Review

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Abstract

Improving nitrogen utilization in dairy cattle is increasingly important due to rising feed costs and the environmental burden associated with nitrogen losses from livestock systems. This systematic review evaluated evidence on precision protein feeding strategies aimed at enhancing nitrogen use efficiency (NUE) in dairy production systems. A total of 1,124 records were initially retrieved from major databases, including Web of Science, Scopus, PubMed, CAB Abstracts, and Google Scholar, alongside supplementary grey literature sources. After duplicate removal and multi-stage screening, 58 studies met the eligibility criteria and were included in the final synthesis. Across the reviewed literature, a consistent pattern emerged showing that excessive crude protein supplementation does not proportionally improve milk production but instead increases nitrogen excretion and feed costs. In contrast, metabolizable protein supply derived from rumen microbial protein, rumen-undegradable protein, and endogenous nitrogen—provides a more functionally relevant indicator of protein availability for productive use in dairy cattle. The synthesis further shows that nitrogen efficiency can be substantially improved through coordinated nutritional interventions. These include balancing limiting amino acids such as lysine and methionine, synchronizing rumen-degradable protein supply with fermentable energy availability, and reducing unnecessary crude protein intake. In addition, controlled-release nitrogen sources such as Optigen® were identified as effective tools for stabilizing ruminal nitrogen availability and improving microbial protein synthesis. Evidence across studies indicates that these precision feeding strategies enhance nitrogen capture in productive pathways while maintaining or improving milk yield and milk protein output. At the same time, reductions in environmentally reactive nitrogen forms—particularly ammonia (NH_3) and nitrous oxide (N_2O) were consistently reported. Overall, the findings demonstrate that improving nitrogen utilization is less dependent on increasing protein supply and more dependent on improving nutrient synchrony and protein quality. Precision protein feeding therefore represents a practical and scalable approach for improving both the economic efficiency and environmental sustainability of dairy production systems.

Keywords

Nitrogen Use Efficiency, Precision Protein Feeding, Dairy Cattle, Metabolizable Protein, Environmental Sustainability

1. Introduction

Dairy production systems are increasingly moving toward precision-based nutritional approaches that aim to better match nutrient supply with animal physiological demand while limiting unnecessary nutrient losses and environmental impacts. Recent advances in precision nutrition emphasize the integration of metabolizable protein systems, amino

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acid balancing, and data-driven feeding strategies to improve nutrient utilization and reduce environmental losses associated with dairy production [2, 17, 32, 34]. Sustainable nitrogen management has become a critical component of modern livestock production because inefficient nitrogen utilization contributes to ammonia emissions, nitrate losses, and greenhouse gas emissions [6, 9, 13].

Among all nutrients, nitrogen (N) has received particular attention because its efficiency of utilization strongly determines milk production efficiency, feeding cost structure, and environmental sustainability outcomes [1, 7]. As dairy production intensifies globally, improving nitrogen use efficiency (NUE) has therefore become both a nutritional and environmental priority. In practice, dairy diets have traditionally been formulated using relatively high crude protein (CP) levels to ensure adequate metabolizable protein (MP) supply and safeguard milk production performance. Although this strategy reduces the risk of nutrient limitation, it often leads to nutrient oversupply under practical farm conditions [32, 35]. Empirical evidence shows that increasing dietary protein beyond animal requirements results in diminishing returns in milk yield while consistently increasing nitrogen excretion, indicating inefficient nutrient capture within productive pathways [1, 15]. From an economic perspective, inefficient nitrogen utilization represents a substantial cost burden in dairy systems because protein supplements are among the most expensive feed components. When nitrogen is not effectively converted into milk protein, a large proportion is lost through urine and feces instead of being retained for productive purposes [7, 32]. Beyond economic inefficiency, these losses also create environmental pressure. Nitrogen released from livestock systems undergoes complex transformations, including ammonia volatilization, nitrate leaching, and nitrous oxide production, which contribute to air pollution, water contamination, and climate change impacts [5, 8, 11, 23, 24].

Urinary nitrogen is rapidly transformed into ammonia (NH_3), contributing to air pollution and ecosystem acidification, while further microbial and biochemical transformations generate nitrous oxide (N_2O), a greenhouse gas with significantly higher warming potential than carbon dioxide [11, 23]. The biological complexity of nitrogen utilization in dairy cattle is largely driven by rumen microbial metabolism. Dynamic modelling approaches have demonstrated that nitrogen utilization depends on interactions among dietary protein fractions, rumen microbial activity, animal metabolism, and environmental losses [12, 26]. Classical ruminant nutrition principles further highlight that efficient microbial protein synthesis requires synchronization between nitrogen availability and fermentable energy supply [31].. After ingestion, dietary protein is partitioned into rumen degradable protein (RDP) and rumen undegradable protein (RUP). RDP supplies nitrogen required for microbial growth and microbial protein synthesis, whereas RUP escapes ruminal degradation and is digested in the small intestine. Together with endogenous protein losses, these fractions determine the total metabolizable protein available for absorption and productive functions such as milk synthesis [20, 27]. Nitrogen efficiency is therefore governed not by protein intake alone, but by the interaction between protein degradation patterns, fermentable energy supply, and amino acid availability. When ruminal nitrogen availability exceeds microbial demand, ammonia accumulates and is converted into urea in the liver, leading to increased urinary nitrogen excretion. Conversely, when nitrogen supply is insufficient, microbial activity declines, fiber digestion is impaired, and microbial protein synthesis is reduced. As a result, synchronization between nitrogen release and energy availability in the rumen is a key determinant of efficient nutrient utilization. Recent developments in precision protein nutrition have shifted attention toward improving coordination between ruminal nitrogen degradation and carbohydrate fermentation, alongside refinement of amino acid balance at the intestinal level. These integrated strategies enhance microbial protein synthesis efficiency, improve metabolizable protein utilization, and reduce nitrogen losses without compromising milk production performance [1, 32]. Consequently, feeding strategies such as reduced crude protein diets, targeted amino acid supplementation, and controlled-release nitrogen sources are increasingly being adopted as practical approaches to improve NUE in dairy systems. Based on this background, the present systematic review synthesizes current scientific evidence on nitrogen utilization in dairy cattle, with emphasis on metabolizable protein dynamics, rumen microbial protein synthesis, and emerging precision feeding strategies designed to enhance nitrogen use efficiency while minimizing environmental impacts.

2. Methods

2.1. Literature Search

This systematic review was designed to consolidate and critically evaluate existing scientific evidence on nitrogen utilization and precision protein nutrition in dairy cattle. The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring a transparent, replicable, and structured approach to study identification, screening, and synthesis [19, 21]. The PRISMA framework was used to organize the identification, screening, eligibility assessment, and inclusion stages of the review process (Figure 1).

The methodological framework comprised several interconnected steps, including development of a comprehensive search strategy, application of predefined eligibility criteria, systematic screening of records, structured data extraction, and qualitative synthesis of findings. This structured approach facilitated a focused assessment of evidence on nitrogen use efficiency and precision feeding strategies in dairy production systems, while also improving consistency across the included studies.

2.2. Literature Search Strategy

A broad and systematic search was conducted across major scientific databases, including Web of Science, Scopus, PubMed, CAB Abstracts, and Google Scholar. These sources were selected to ensure comprehensive coverage of peer-reviewed literature in animal nutrition and ruminant metabolism. To minimize publication bias and capture additional relevant evidence, grey literature sources such as conference proceedings, institutional reports, postgraduate theses, and technical documents were also included.

The search was limited to studies published between 2000 and 2025 to capture both foundational concepts and recent advancements in nitrogen metabolism, metabolizable protein systems, and precision feeding approaches [10, 20]. Key terms were combined using Boolean operators ("AND" and "OR") to improve search precision. The main keywords included: "nitrogen use efficiency," "metabolizable protein," "rumen degradable protein," "rumen undegradable protein," "amino acid balancing," "precision feeding," "dairy cattle," and "nitrogen excretion."

Search strings were adapted slightly for each database to account for differences in indexing systems and search interfaces, while maintaining consistency in conceptual focus across all platforms.

2.3. Eligibility Criteria

Eligibility criteria were defined prior to screening to ensure consistency and relevance to the research objectives. Included studies comprised peer-reviewed journal articles, conference papers, and technical reports focusing on protein nutrition and nitrogen metabolism in dairy cattle. Studies addressing nitrogen use efficiency, milk production responses, nitrogen excretion pathways, and precision feeding strategies were considered relevant.

Both experimental approaches (in vivo and in vitro studies) and modeling-based studies were included, provided they contributed quantitative or mechanistic insights into nitrogen utilization processes [3, 4].

Studies were excluded based on the following conditions:

1) Non-ruminant species focus
2) Lack of quantitative or mechanistic relevance to nitrogen metabolism
3) Duplicate datasets or repeated publications
4) Review articles, books, book chapters, or abstracts without primary data
5) Non-English publications
6) The predefined inclusion and exclusion criteria applied during screening are summarized in Table 1.

2.4. Study Selection Process

The study selection followed a structured PRISMA-guided procedure consisting of four sequential stages: identification, screening, eligibility assessment, and final inclusion. Initially, all records retrieved from the databases were imported into reference management software, where duplicate entries were systematically removed.

In the next stage, titles were screened to exclude clearly irrelevant studies. Remaining articles underwent abstract screening to assess thematic alignment with nitrogen utilization and dairy protein nutrition. Finally, full-text articles were carefully reviewed to confirm eligibility based on predefined criteria (Table 3).

This multi-stage selection process enhanced transparency, reduced selection bias, and ensured methodological rigor throughout the review process (Moher et al., 2009; Page et al., 2021). The overall workflow is summarized in the PRISMA flow diagram (Figure 1).

Table 1. *Inclusion and Exclusion Criteria.*

Criterion	Eligibility	Exclusion
Literature type	Journal articles, conference papers, technical reports	Books, book chapters, unrelated reviews
Language	English	Non-English
Time frame	2000-2025	Outside selected years
Species	Dairy cattle and ruminants	Non-ruminants
Accessibility	Full-text available	Full-text unavailable

2.5. Research Questions

Three research questions were formulated to guide the evidence synthesis (Table 2). These questions were designed to capture both nutritional mechanisms and applied implications of nitrogen use efficiency (NUE) in dairy cattle systems.

Table 2. Research Questions.

Research Questions (RQ)	Description
RQ1	What are the main nutritional strategies that influence nitrogen use efficiency in dairy cattle?
RQ2	How do metabolizable protein, rumen degradable protein, and rumen undegradable protein affect milk production and nitrogen utilization?
RQ3	What are the key research gaps and future directions in precision protein nutrition and environmental sustainability in dairy systems?

2.6. Systematic Review Process

The study selection followed the PRISMA framework and was implemented through four sequential stages: identification, screening, eligibility assessment, and final inclusion. This structured procedure was used to ensure transparency, traceability, and reproducibility throughout the review process.

In the first stage, all records retrieved from different databases were imported into reference management software, where duplicate entries were systematically identified and removed. The remaining records were then subjected to title screening to eliminate studies that were clearly unrelated to nitrogen utilization or dairy protein nutrition.

Next, abstracts were reviewed to assess thematic relevance to precision protein nutrition, metabolizable protein systems, and nitrogen use efficiency in dairy cattle. Studies that passed this stage were further examined at full-text level against the predefined eligibility criteria to confirm their suitability for inclusion.

The database-specific search strategy is presented in Table 3, whereas the overall study selection procedure is illustrated in Figure 1.

Overall, this structured PRISMA-guided approach improved methodological rigor, reduced selection bias, and ensured systematic documentation of all inclusion decisions (Moher et al., 2009; Page et al., 2021).

Table 3. Search Strings Used for the Systematic Review.

Database	Search Area	Keywords / Search Strings
Web of Science	Topic	“nitrogen use efficiency” AND “dairy cattle”
Scopus	Title, Abstract, Keywords	“precision feeding” OR “metabolizable protein”
PubMed	Advanced Search	“rumen degradable protein” AND “nitrogen excretion”
Google Scholar	Full Search	“precision protein nutrition in dairy cattle”
CAB Abstracts	Topic Search	“amino acid balancing” AND “milk protein synthesis”

2.7. Data Extraction and Analysis

Data extraction was carried out using a structured Microsoft Excel template specifically developed for this review. For each included study, key information was systematically recorded, including publication year, geographic location, experimental design, dietary protein composition, crude protein levels, rumen degradable protein (RDP), rumen undegradable protein (RUP), amino acid profile, milk yield, milk protein content, and indicators of nitrogen utilization efficiency and nitrogen excretion.

The extraction process began with abstract-level screening, followed by full-text review to ensure accurate capture of relevant methodological and outcome variables. Extracted data were then synthesized qualitatively to identify major themes and emerging patterns across studies.

Where appropriate, findings from experimental studies were compared with results from modeling approaches to assess consistency and explain observed variation in nitrogen utilization responses [8, 26]. This comparative synthesis strengthened interpretation at both mechanistic and system levels.

2.8. Quality Assessment

The methodological quality of the included studies was evaluated using predefined criteria focusing on experimental rigor, sample size adequacy, replication level, clarity of dietary treatments, and reliability of laboratory and analytical methods. Studies were categorized as high, moderate, or low quality based on predefined methodological criteria.

Based on these criteria, studies were categorized as high, moderate, or low quality. During synthesis and interpretation, greater analytical weight was given to studies with stronger experimental design and higher methodological reliability (Sinclair et al., 2014; NASEM, 2021).

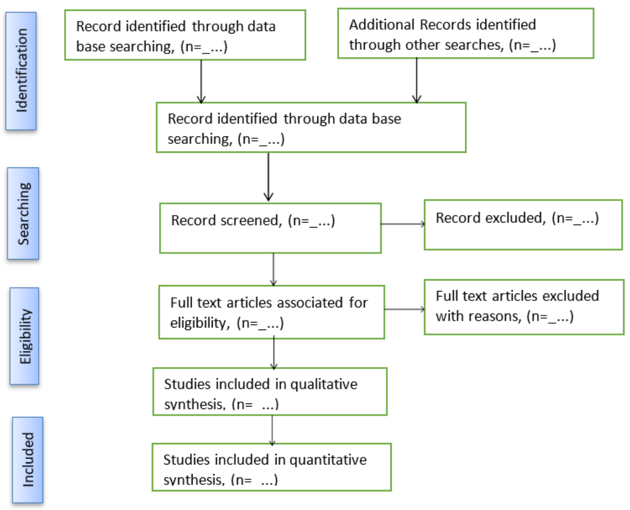

Figure 1. The PRISMA flow diagram.

3. Results

3.1. Literature Search Results

The study selection followed the PRISMA guidelines to ensure a transparent and reproducible review process [19, 21]. The comprehensive search across Web of Science, Scopus, PubMed, CAB Abstracts, Google Scholar, and grey literature sources initially identified 895 records related to nitrogen utilization, metabolizable protein, rumen nitrogen metabolism, and precision feeding strategies in dairy cattle.

After removing duplicates using reference management software, the remaining records were screened based on titles and abstracts to assess relevance to nitrogen use efficiency (NUE), protein nutrition, and environmental sustainability in dairy systems. Studies focusing on non-ruminants, non-relevant nutritional topics, reviews, conference abstracts without primary data, and inaccessible full texts were excluded according to predefined criteria.

Following full-text assessment, 67 studies were retained for detailed evaluation, of which 58 studies met all inclusion criteria and were included in the final synthesis (Figure 2). This selection reflects a focused body of literature directly addressing precision protein nutrition and nitrogen utilization in dairy cattle.

Overall, the included studies covered key themes such as dietary crude protein regulation, rumen degradable protein (RDP), rumen undegradable protein (RUP), metabolizable protein (MP), amino acid balancing, microbial protein synthesis, nitrogen excretion pathways, and emerging precision feeding technologies aimed at improving NUE.

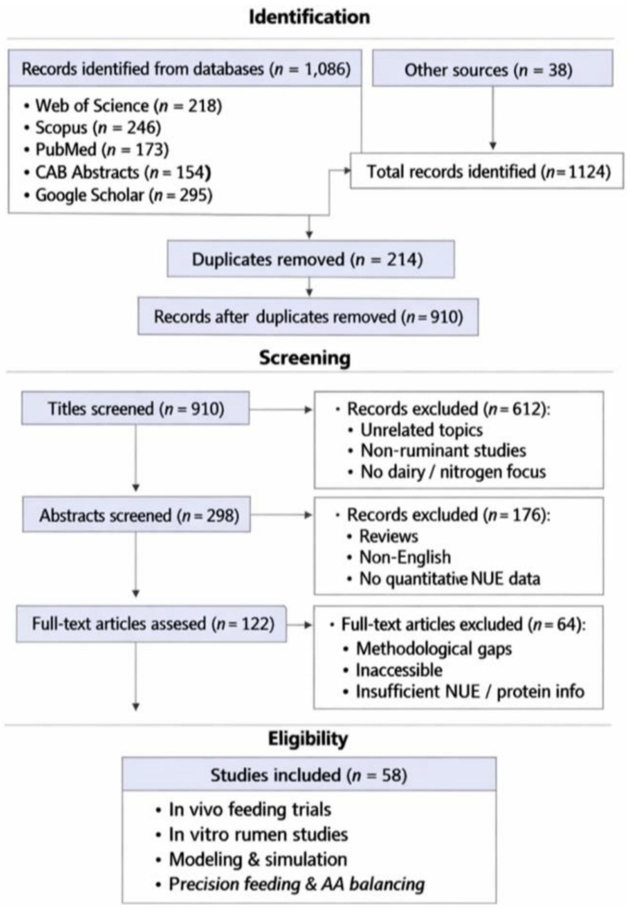

Figure 2. Flow chart of study selection process.

3.2. Study Characteristics

This review synthesized evidence from studies published between 2000 and 2025, focusing exclusively on peer-reviewed research articles to ensure methodological consistency and comparability. Non-research publications such as books, reviews, and abstracts without primary data were excluded.

A total of 58 studies were included in the final analysis (Figure 1). A clear temporal pattern emerged, with a marked increase in publications after 2010 and a rapid expansion in the last decade. This reflects a broader shift in dairy nutrition research from crude protein-based formulation toward metabolizable protein systems, amino acid balancing, and precision nitrogen management.

The distribution of studies across journal categories is summarized in Table 4.

Table 4. *Distribution of included studies by journal category and publication period.*

Journal category	Representative journals	Main focus	Trend (2000-2025)
A High-impact animal science journals	Journal of Dairy Science, Animal, Journal of Animal Science, Animal Feed Science and Technology	Dairy nutrition, nitrogen metabolism, precision feeding	Dominant and steadily increasing
B Applied nutrition journals	Journal of Dairy Research, Livestock Science, British Journal of Nutrition, Animal Nutrition	Protein efficiency, rumen function	Stable contribution
C Agricultural/environmental journals	Science of the Total Environment, Agricultural Systems, PLoS ONE, Sustainability	Nitrogen losses, environmental impacts	Strong growth after 2015
D Specialized/technical journals	Biotechnology, modeling, environmental journals	Microbial processes, nitrogen cycling	Gradual increase
Grey literature	Theses, reports, technical documents	Applied dairy systems	Limited but useful

Overall, high-impact animal science journals remain the primary source of evidence, although environmental and systems-based research has increased notably, reflecting growing concern for sustainability alongside productivity.

3.3. Overview of the Reviewed Literature

The literature shows a consistent upward trend in research attention toward nitrogen utilization efficiency and precision protein nutrition in dairy cattle between 2000 and 2025. Early work was largely concentrated in North America and Europe, where advanced feeding systems and environmental regulations drove early adoption of nutrient optimization strategies [8, 20].

More recent studies from Asia indicate growing interest in sustainable dairy nutrition and emission reduction strategies [32]. However, research from African dairy systems remains limited, particularly under smallholder and tropical conditions, highlighting a clear geographic knowledge gap.

Recent modelling studies have increasingly contributed to evaluating nitrogen flows, economic trade-offs, and environmental consequences of alternative feeding strategies at farm and system levels [10, 12, 14]. Despite methodological differences, these studies converge on a common conclusion: improving nitrogen use efficiency requires better synchronization of dietary nitrogen supply with microbial and metabolic demand.

This progression also reflects a conceptual shift from crude protein-centered feeding toward metabolizable protein (MP)-based and amino acid-oriented nutritional models.

Table 5. *General Characteristics of the Reviewed Studies.*

Study Category	Main Focus	Common Outcomes
In vivo feeding trials	Dietary protein manipulation	Milk yield, nitrogen excretion responses
In vitro rumen studies	Fermentation dynamics	Ammonia production, microbial protein synthesis
Modeling studies	System-level evaluation	Environmental and economic performance
Precision feeding studies	Amino acid balancing	Improved NUE, reduced N losses

3.4. Concepts of Nitrogen Utilization in Dairy Cattle

Nitrogen use efficiency (NUE) refers to the proportion of dietary nitrogen converted into productive outputs, mainly milk protein, rather than being lost through excretion [10, 20]. Improving NUE is increasingly recognized as a central goal because it links animal productivity, feed efficiency, and environmental sustainability.

In ruminants, nitrogen metabolism is primarily regulated by rumen microbial fermentation. Dietary protein is degraded into rumen degradable protein (RDP), which supports microbial growth, while rumen undegradable protein (RUP) bypasses the rumen and is digested in the small intestine [3, 27]. Together with microbial crude protein (MCP) and endogenous contributions, these fractions determine metabolizable protein

(MP), the actual protein available for absorption and production [20].

Nitrogen efficiency is therefore governed not only by total protein intake but by the balance between protein fractions, fermentable energy, and amino acid supply. Excess nitrogen is converted to urea and excreted, contributing to environmental losses such as ammonia volatilization, nitrate leaching, and nitrous oxide emissions [8, 23].

Table 6. *Major Concepts of Nitrogen Utilization in Dairy Cattle.*

Concept	Description	Importance
NUE	Efficiency of nitrogen conversion to milk protein	Production & environmental indicator
RDP	Rumen-degraded protein	Microbial growth support
RUP	Bypass protein	Amino acid supply
MCP	Microbial protein	Major amino acid source
MP	Absorbable protein	Milk synthesis support
MUN	Milk urea nitrogen	Diet balance indicator

3.5. Dietary Crude Protein and NUE

Across studies, dietary crude protein (CP) level consistently emerged as a primary driver of nitrogen efficiency. High-CP diets were repeatedly associated with elevated milk urea nitrogen (MUN) concentrations and increased urinary nitrogen losses, with little or no improvement in milk yield [3, 7].

This indicates inefficient nitrogen capture, whereby excess dietary protein is converted into urea and excreted, resulting in both economic losses and increased environmental pollution risks [22].

In contrast, moderate reductions in dietary CP, when combined with appropriate energy supply and amino acid balance, were shown to maintain milk production while improving nitrogen retention efficiency [15, 32].

Table 7. *Effects of Dietary Protein Level on Nitrogen Utilization.*

Condition	Production Response	Nitrogen Loss
Excess CP	Slight/no milk gain	High urinary N
Balanced CP	Stable production	Improved retention
CP reduction + AA balance	Stable milk protein	Reduced losses
Imbalance	Poor efficiency	High ammonia/urea

3.6. Rumen Protein Fractions and Microbial Efficiency

The balance between rumen degradable protein (RDP) and rumen undegradable protein (RUP) plays a central role in nitrogen utilization efficiency. Previous research has demonstrated that inappropriate synchronization between ruminal nitrogen release and carbohydrate fermentation reduces microbial protein capture and increases nitrogen losses [4, 12, 31].

Adequate RDP supports microbial protein synthesis, which is a major source of metabolizable protein [20].

However, excess RDP leads to ammonia accumulation and increased urinary nitrogen losses [8]. Conversely, insufficient RUP restricts amino acid supply to high-producing dairy cows [27].

Optimal nitrogen efficiency is achieved when rumen nitrogen release is synchronized with carbohydrate fermentation, improving microbial protein capture and reducing nitrogen losses.

Table 8. *Functional Roles of RDP and RUP.*

Fraction	Function	Imbalance Effect
RDP	Microbial support	Ammonia excess
RUP	Amino acid supply	Production limits
Balanced ratio	Efficient synthesis	Improved NUE

3.7. Metabolizable Protein and Amino Acid Balancing

Metabolizable protein (MP) provides a more accurate representation of usable dietary protein than crude protein systems [20]. It reflects absorbed amino acids available for maintenance and milk production.

Lysine and methionine were consistently identified as the first-limiting amino acids in dairy cows [16, 29]. Optimizing essential amino acid supply allows reductions in dietary crude protein while maintaining milk protein production and improving nitrogen retention efficiency [2, 28, 34, 36]. Their supplementation improves milk protein yield and nitrogen efficiency even at reduced crude protein levels.

Table 9. *Benefits of MP-Based Feeding.*

Strategy	Benefit
CP-based feeding	Simple but less precise
MP-based feeding	More biologically accurate
Amino acid balancing	Higher efficiency
Precision feeding	Lower nitrogen loss

3.8. Production Trade-offs and Precision Feeding

Precision feeding strategies that synchronize amino acid supply with energy availability can maintain milk yield while improving nitrogen efficiency. Recent studies indicate that precision ration formulation and targeted nutrient delivery can simultaneously improve productivity, economic efficiency, and environmental performance [17, 18, 30, 35-37]. However, this trade-off is not biological but nutritional in origin.

Precision feeding strategies that synchronize amino acid supply with energy availability can maintain milk yield while improving nitrogen efficiency and reducing nitrogen excretion [1, 35].

3.9. Environmental Implications of Nitrogen Loss

Urinary nitrogen is rapidly converted into ammonia, nitrate, and nitrous oxide, creating environmental impacts that extend beyond the farm boundary. These nitrogen pathways are major contributors to atmospheric pollution, eutrophication, and greenhouse gas emissions from livestock systems [5, 9, 13, 23-25, 33]. A consistent relationship was observed between high dietary protein intake and increased nitrogen emissions [11].

Table 10. *Environmental Impacts of Nitrogen Loss.*

Pathway	Impact
Ammonia	Air pollution
Nitrate	Water contamination
N_2O	Climate change
Manure N	Eutrophication

3.10. Modeling Insights

Modeling studies consistently show that reducing dietary crude protein while maintaining amino acid balance improves both economic and environmental performance. Process-based and farm-scale models have demonstrated that integrated nitrogen management can reduce emissions while maintaining animal productivity [10, 12, 14, 22]. Synchronization of rumen nitrogen and energy supply improves microbial protein synthesis efficiency [4].

Nitrogen efficiency is driven by interactions among dietary composition, rumen microbial activity, and systemic metabolism [20, 26]. The most effective strategies combine reduced crude protein intake, optimized RDP balance, amino acid supplementation, and energy synchronization [1, 32].

4. Discussion

Findings confirm that excessive crude protein intake is a major driver of nitrogen inefficiency, increasing nitrogen excretion without proportional improvements in milk production. Similar conclusions have been reported across experimental, modelling, and farm-scale studies emphasizing improved protein precision rather than increased protein supply [7, 15, 18, 22, 27]. The shift toward metabolizable protein and amino acid-based nutrition reflects improved biological accuracy in diet formulation [20].

4.1. Conclusion

This review demonstrates that improving nitrogen use efficiency (NUE) in dairy cattle relies primarily on enhancing the accuracy of protein utilization rather than increasing dietary crude protein levels. Across the reviewed studies, excessive protein supply was consistently linked with increased nitrogen losses and limited gains in milk production. In contrast, strategies that improve amino acid balance, optimize rumen microbial activity, and synchronize nitrogen and energy availability enhance the conversion of dietary nitrogen into milk protein.

The available evidence supports a shift from conventional crude protein-based ration formulation toward metabolizable protein and amino acid-based feeding approaches that more closely match animal requirements. Such targeted nutritional management can improve feed efficiency, reduce nitrogen emissions, and contribute to more environmentally sustainable dairy production systems.

4.2. Future Directions

Although substantial progress has been made in understanding nitrogen metabolism and improving protein utilization, several research gaps remain. Current evidence is largely derived from intensive dairy systems in developed regions, while knowledge from tropical, smallholder, and low-input production systems is still limited. Future studies should therefore focus on developing context-specific feeding strategies that incorporate differences in feed resources, climate conditions, animal characteristics, and farm management practices.

Further long-term field evaluations are needed to assess the economic feasibility, environmental benefits, and practical adoption of precision protein feeding under diverse production conditions. Emerging technologies, including digital monitoring tools, predictive models, and automated feeding systems, may further improve nutrient management and support real-time dietary optimization.

Future research should also adopt integrated approaches that link nitrogen efficiency with greenhouse gas mitigation, animal health, reproductive performance, and climate resilience. Combining nutritional innovations with environmental assessment and technological advancement will be critical for developing dairy systems that achieve higher productivity while reducing ecological impacts. Overall, precision protein nutrition offers a promising pathway toward more efficient, profitable, and sustainable dairy production.

Abbreviations

AA	Amino Acid
CP	Crude Protein
DM	Dry Matter
DMI	Dry Matter Intake
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse Gas
MCP	Microbial Crude Protein
MP	Metabolizable Protein
MUN	Milk Urea Nitrogen
N	Nitrogen
N_2O	Nitrous Oxide
NH_3	Ammonia
NASEM	National Academies of Sciences, Engineering, and Medicine
NUE	Nitrogen Use Efficiency
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RDP	Rumen Degradable Protein
RDP	Ratio of Rumen Degradable Protein to Rumen Undegradable Protein
RUP	Rumen Undegradable Protein

Author Contributions

Genet Dadi Hailu: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing

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Data Availability Statement

The data that supports the write up of this review are available from the corresponding author, upon reasonable request

All authors read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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