

MILK UREA NITROGEN BEYOND NUTRITION: INTEGRATION WITH METABOLIC, BEHAVIORAL, AND WELFARE INDICATORS IN DAIRY CATTLE: A NARRATIVE REVIEW

NITROGÊNIO UREICO NO LEITE ALÉM DA NUTRIÇÃO: INTEGRAÇÃO COM INDICADORES METABÓLICOS, COMPORTAMENTAIS E DE BEM-ESTAR EM BOVINOS LEITEIROS: REVISÃO NARRATIVA

NITRÓGENO UREICO EN LECHE MÁS ALLÁ DE LA NUTRICIÓN: INTEGRACIÓN CON INDICADORES METABÓLICOS, COMPORTAMENTALES Y DE BIENESTAR EN BOVINOS LECHEROS: REVISIÓN NARRATIVA

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ABSTRACT

Milk urea nitrogen is routinely measured in dairy herds and is widely used to assess protein-energy balance and nitrogen use efficiency. This narrative review evaluated its potential role as an integrative indicator when interpreted alongside metabolic, inflammatory, behavioral, and precision-farming information. Peer-reviewed literature published mainly from 2016 to 2026 was examined, prioritizing studies on nitrogen metabolism, blood biomarkers, behavioral monitoring, animal welfare, and automated sensing. Evidence confirms that milk urea nitrogen is influenced by dietary protein, fermentable energy, urea recycling, hepatic metabolism, individual efficiency, and urinary nitrogen losses. Independently, metabolic stress, inflammation, heat load, pain, and clinical disorders are associated with changes in endocrine and inflammatory markers, leukocyte profiles, rumination, feeding, activity, and lying behavior. However, current evidence does not

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support using milk urea nitrogen as a direct marker of stress, pain, or disease. Its main value lies in contextual interpretation: persistent deviations may identify nutritional or metabolic situations that warrant evaluation with production records, clinical examination, blood biomarkers, and sensor-derived behavior. Integrating these data streams may improve herd screening, nitrogen-management decisions, and early identification of animals requiring closer assessment, but prospective studies are needed to validate thresholds, temporal relationships, and predictive models across production systems.

Keywords: Animal Health. Environmental Sustainability. Precision Livestock Farming. Protein-Energy Balance. Rumination.

RESUMO

O nitrogênio ureico no leite é mensurado rotineiramente em rebanhos leiteiros e amplamente utilizado para avaliar o balanço proteína-energia e a eficiência de utilização do nitrogênio. Esta revisão narrativa avaliou seu potencial como indicador integrativo quando interpretado em conjunto com informações metabólicas, inflamatórias, comportamentais e de pecuária de precisão. Foram examinadas publicações científicas, principalmente entre 2016 e 2026, priorizando estudos sobre metabolismo do nitrogênio, biomarcadores sanguíneos, monitoramento comportamental, bem-estar animal e sensoriamento automatizado. As evidências confirmam que o nitrogênio ureico no leite é influenciado pela proteína da dieta, energia fermentescível, reciclagem da ureia, metabolismo hepático, eficiência individual e perdas urinárias de nitrogênio. De forma independente, estresse metabólico, inflamação, carga térmica, dor e distúrbios clínicos estão associados a alterações em marcadores endócrinos e inflamatórios, perfil leucocitário, ruminação, alimentação, atividade e tempo deitado. Entretanto, as evidências atuais não sustentam o uso do nitrogênio ureico no leite como marcador direto de estresse, dor ou doença. Seu principal valor está na interpretação contextual, em que desvios persistentes podem indicar situações nutricionais ou metabólicas que justificam avaliação com registros produtivos, exame clínico, biomarcadores sanguíneos e comportamento obtido por sensores. A integração dessas informações pode aprimorar a triagem do rebanho e o manejo do nitrogênio, mas estudos prospectivos são necessários para validar relações temporais e modelos preditivos em diferentes sistemas de produção.

Palavras-chave: Balanço Proteína-Energia. Pecuária de Precisão. Ruminação. Saúde Animal. Sustentabilidade Ambiental.

RESUMEN

El nitrógeno ureico en la leche se mide de forma rutinaria en los rebaños lecheros y se utiliza ampliamente para evaluar el balance proteína-energía y la eficiencia de utilización del nitrógeno. Esta revisión narrativa evaluó su potencial como indicador integrador cuando se interpreta junto con información metabólica, inflamatoria, conductual y de ganadería de precisión. Se examinaron publicaciones científicas, principalmente entre 2016 y 2026, priorizando estudios sobre metabolismo del nitrógeno, biomarcadores sanguíneos, monitoreo del comportamiento, bienestar animal y sensores automatizados. La evidencia confirma que el nitrógeno ureico en la leche está influido por la proteína de la dieta, la energía fermentable, el reciclaje de urea, el metabolismo hepático, la eficiencia individual y las pérdidas urinarias de nitrógeno. De manera independiente, el estrés metabólico, la inflamación, la carga térmica, el dolor y los trastornos clínicos se asocian

con cambios en marcadores endocrinos e inflamatorios, perfiles leucocitarios, rumia, alimentación, actividad y tiempo de descanso. Sin embargo, la evidencia actual no respalda su uso como marcador directo de estrés, dolor o enfermedad. Su principal valor reside en la interpretación contextual, en la que desviaciones persistentes pueden señalar situaciones nutricionales o metabólicas que requieren evaluación mediante registros productivos, examen clínico, biomarcadores sanguíneos y comportamiento obtenido por sensores. La integración de estas fuentes de información puede mejorar el cribado del rebaño y el manejo del nitrógeno, aunque se necesitan estudios prospectivos para validar relaciones temporales y modelos predictivos en diferentes sistemas de producción.

Palabras-clave: Balance Proteína-Energía. Ganadería de Precisión. Rumiación. Salud Animal. Sostenibilidad Ambiental.



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INTRODUCTION

Dairy production increasingly depends on tools that jointly support nutritional precision, herd health, animal welfare, and environmental efficiency. Precision livestock farming has expanded the capacity to monitor production and animal-based indicators continuously, but the usefulness of these technologies still depends on biologically meaningful interpretation (Lovarelli *et al.*, 2020; Kleen; Guatteo, 2023). In this context, variables already available through routine milk recording are especially attractive because they can be incorporated into herd monitoring without adding handling procedures or substantial sampling costs.

Milk urea nitrogen (MUN) is one of these variables. It has traditionally been interpreted as an indicator of dietary protein supply, rumen-degradable protein, fermentable energy availability, and nitrogen use efficiency. Experimental evidence also supports associations with urinary nitrogen excretion and with traits related to nitrogen efficiency, making MUN relevant to nutritional management and to the environmental footprint of dairy production (Barros *et al.*, 2019; Bobbo *et al.*, 2020).

The biological interpretation of MUN is nevertheless broader than a direct reflection of dietary crude protein. Differences among cows can arise from gastrointestinal urea transport, hepatic urea metabolism, urea recycling, and individual nitrogen-use phenotypes (Souza *et al.*, 2021; Prah *et al.*, 2022). Milk-based phenotyping can also capture information related to nitrogen efficiency and metabolic status, which reinforces the potential value of milk variables

in precision-nutrition strategies (Grelet *et al.*, 2020; De Koster *et al.*, 2019).

At the same time, health and welfare assessment in dairy cattle increasingly integrates blood biomarkers, clinical findings, and behavior. Metabolic and inflammatory challenges can alter endocrine, immune, and oxidative responses, whereas rumination, feeding, activity, and lying behavior may change before or around the clinical recognition of disease (Putman *et al.*, 2018; Stangaferro *et al.*, 2016a, 2016b, 2016c). However, evidence directly linking MUN to stress, pain, disease, or welfare outcomes remains limited. Therefore, MUN should not be treated as a stand-alone diagnostic biomarker for these conditions.

This narrative review aims to examine MUN beyond its conventional nutritional interpretation, synthesize evidence on complementary physiologic, behavioral, welfare, and precision-monitoring indicators, and propose a cautious framework for integrating these data in dairy-herd assessment. The central premise is that MUN may function as a nutritional-metabolic sentinel whose meaning becomes more informative when interpreted together with independent indicators of health and welfare.

MATERIALS AND METHODS

This narrative review was based on peer-reviewed literature addressing milk urea nitrogen, nitrogen metabolism and use efficiency, physiological and health indicators, behavioral and welfare measures, and precision livestock farming in dairy cattle. A structured, non-systematic literature search was conducted in Scopus, Web of Science Core Collection, PubMed, and SciELO, with emphasis on studies published between 2016 and 2026.

To accommodate the multidisciplinary scope of the review and avoid excessive restriction of the literature search, search terms were organized into four thematic blocks rather than combined into a single search string. Each search included terms describing the target population (“dairy cows”, “dairy cattle”, and “lactating cows”) combined with terms related to: (i) MUN and nitrogen metabolism (“milk urea nitrogen”, “milk urea”, “nitrogen use efficiency”, “nitrogen utilization”, and “nitrogen metabolism”); (ii) physiological and health indicators (“stress biomarkers”, “cortisol”, “metabolic biomarkers”, “inflammatory biomarkers”, “inflammation”, and “physiological indicators”); (iii) behavioral and welfare indicators (“rumination”, “activity monitoring”, “feeding behavior”, “lying behavior”, and “animal welfare”); and (iv) precision monitoring and data integration (“precision livestock farming”, “precision dairy farming”,

“automated monitoring”, “accelerometers”, “wearable sensors”, “computer vision”, “machine learning”, “artificial intelligence”, and “data integration”). Synonymous terms within each conceptual block were combined using the Boolean operator OR, whereas the dairy-cattle population block was combined with each thematic block using AND.

Database searches focused on publications from 2016 to 2026. Older seminal publications were additionally identified through backward citation searching and were retained when necessary to support established methodological principles, biological mechanisms, or concepts that remained relevant to the interpretation of more recent evidence. Reference lists of relevant articles were also examined to identify additional studies not retrieved in the primary database searches.

Because the purpose of the review was narrative and interpretive rather than systematic, no formal meta-analysis, risk-of-bias assessment, or PRISMA-based study-selection process was performed. Evidence was critically synthesized and organized into five overarching themes: nitrogen metabolism; physiological and health indicators; behavioral and welfare indicators; precision monitoring and data integration; and current research gaps and perspectives.

MILK UREA NITROGEN AS A NUTRITIONAL AND ENVIRONMENTAL INDICATOR

MUN reflects the transfer of urea from blood to milk and is influenced by the amount and degradability of dietary protein, ruminal ammonia production, fermentable carbohydrate availability, hepatic ureagenesis, urea recycling, and routes of nitrogen excretion. In practical nutrition, elevated values may occur when degradable nitrogen supply exceeds the capacity of rumen microorganisms to capture ammonia, particularly when fermentable energy is insufficient for microbial protein synthesis. Conversely, lower values may occur with limited nitrogen supply or reduced intake. These interpretations are useful, but they should be applied in the context of the diet, production level, and the individual animal rather than as universal diagnostic cutoffs (Bobbo *et al.*, 2020; Souza *et al.*, 2021).

The environmental relevance of MUN derives from its relationship with inefficient nitrogen use. In late-lactation cows receiving nitrogen-limiting diets, Barros *et al.* (2019) showed that MUN could predict urinary nitrogen and urinary urea nitrogen excretion within the conditions evaluated. This relationship is important because urinary nitrogen is a major pathway

through which surplus dietary nitrogen is lost from dairy systems. Thus, MUN can support ration evaluation while also contributing to herd-level strategies aimed at reducing nitrogen losses.

Individual variation is a central limitation and, at the same time, an informative component of MUN. Souza *et al.* (2021) demonstrated that gastrointestinal urea transport contributes to differences in MUN among lactating cows. Prah *et al.* (2022) reported differences in hepatic urea, creatinine, and uric acid metabolism in cows with divergent milk urea concentrations, indicating that MUN reflects systemic metabolic processes rather than dietary input alone. Bobbo *et al.* (2020) additionally described genetic aspects of MUN and proposed derived traits related to nitrogen efficiency.

Other milk-based approaches reinforce this broader interpretation. Grelet *et al.* (2020) showed that milk mid-infrared spectra can be used to predict nitrogen use efficiency in individual cows, whereas De Koster *et al.* (2019) demonstrated that milk biomarkers can contribute to the identification of metabolic clusters in early lactation. Together, these studies support the concept that milk can serve as a low-burden biological matrix for precision phenotyping. Nevertheless, MUN remains most robustly supported as a nutritional and nitrogen-efficiency indicator; extending its interpretation to health or welfare requires independent corroborating information.

COMPLEMENTARY PHYSIOLOGIC, HEALTH, AND WELFARE INFORMATION

Metabolic Stress and Blood Biomarkers

Physiologic stress in dairy cattle involves coordinated endocrine, immune, metabolic, and oxidative responses. Heat load, inflammatory disease, transition periods, and nutritional challenges can increase maintenance demands and alter metabolism, reproduction, and production (Collier *et al.*, 2017). Putman *et al.* (2018) documented changes in biomarkers of nutrient metabolism, inflammation, and oxidative stress during the transition into the early dry period, illustrating how homeostatic changes can be detected before they are fully expressed in production outcomes.

Experimental challenges also demonstrate the overlap between nutrition and inflammation. Xu *et al.* (2017) showed that a grain challenge altered systemic and hepatic molecular biomarkers of inflammation, stress, and metabolism, with differences between Holstein and Jersey cows. Aditya *et al.* (2018) reported metabolic and stress responses when

dairy cows receiving a concentrate-rich diet were exposed to an intramammary inflammatory challenge. These findings are relevant to MUN interpretation because nutritional imbalance and systemic stress can coexist, but they do not establish MUN as a direct stress marker.

In an integrative framework, variables such as cortisol, glucose, creatine kinase, acute-phase proteins, and leukocyte profiles can provide complementary information when a nutritional signal is persistent or inconsistent with expected herd performance. The proposed role of these biomarkers is contextual: they can help determine whether an abnormal MUN pattern is accompanied by a broader physiologic disturbance. This combined interpretation remains a research framework rather than a validated diagnostic rule.

Clinical and Welfare Indicators

Animal welfare is multidimensional and cannot be inferred from a single milk or blood measurement. Reviews of dairy-cow welfare emphasize animal-based indicators such as body condition, lameness, mastitis, behavior, and other measures of health and affective state, while also considering the practicality and validity of each measure under commercial conditions (Silva *et al.*, 2021; Linstädt *et al.*, 2024). Comparisons between pasture-based and confinement systems likewise show that welfare outcomes depend on multiple interacting advantages and risks rather than on one management feature alone (Mee; Boyle, 2020; Córdoba *et al.*, 2026).

Recent work on non-invasive physiologic indicators further supports a multi-indicator approach. Kremer *et al.* (2026) evaluated hair cortisol, heart-rate variability, and milk-yield characteristics as potential welfare indicators, reinforcing the need to interpret physiologic measures within an explicit welfare framework. Accordingly, high or low MUN should not be considered proof of impaired welfare. Its welfare relevance is indirect and becomes more plausible only when nutritional-metabolic deviations coincide with altered body condition, disease, reduced performance, or other animal-based indicators.

Pain-related measures may also contribute to welfare assessment, although they require rigorous standardization. Pressure algometry has been evaluated for quantifying mechanical nociceptive threshold in lactating cows and calves, with studies emphasizing the influence of measurement conditions and the need for repeatable protocols (Krug *et al.*, 2018; Williams *et al.*, 2020). At present, there is no evidence supporting a causal relationship between MUN and mechanical nociceptive threshold. Pain sensitivity should therefore be treated as an independent

exploratory welfare outcome rather than as a consequence of MUN status.

BEHAVIOR AS AN EARLY, NONSPECIFIC SIGNAL

Rumination, Feeding, Lying, and Activity

Behavioral monitoring provides continuous, animal-based information that can complement intermittent milk and blood measurements. Rumination and activity data have been used to identify cows with metabolic and digestive disorders, mastitis, and metritis, with deviations sometimes occurring before or close to clinical diagnosis (Stangaferro *et al.*, 2016a, 2016b, 2016c). Steensels *et al.* (2016) also showed that combinations of rumination, activity, milk yield, body weight, and voluntary visits to an automatic milking system can contribute to post-calving disease detection.

Behavioral variables are sensitive but not disease-specific. Thorup *et al.* (2016) found that lameness altered feeding behavior even when rumination was not clearly affected. Borchers *et al.* (2016) validated technologies for monitoring feeding, rumination, and lying behavior against direct observation, while Stone *et al.* (2017) demonstrated that breed, milk yield, and the temperature-humidity index influence lying time, activity, reticulorumen temperature, and rumination. These results show that behavioral alerts must be interpreted in relation to environmental and individual covariates.

Gusterer *et al.* (2020) described rumination duration and activity as nonspecific variables for the early detection of health deviations. This nonspecificity is clinically useful for screening but limits etiologic interpretation. A fall in rumination or an increase in inactivity indicates that closer examination may be justified; it does not establish the underlying cause.

Interpretation Alongside Milk Urea Nitrogen

The temporal integration of MUN and behavior is conceptually attractive because the two information streams describe different biological domains. MUN primarily reflects nitrogen metabolism and nutritional efficiency, whereas rumination, feeding, activity, and lying behavior provide nonspecific information on animal state. A persistent MUN deviation accompanied by a concurrent behavioral change should therefore be interpreted as a reason to investigate diet,

health, and environmental conditions, not as a combined diagnostic test.

Conversely, a herd with persistently high MUN but stable intake-related behavior, normal production, and no clinical or inflammatory abnormalities may require nutritional reformulation without evidence of a broader welfare problem. This distinction is important because the value of an integrative approach lies in reducing false biological interpretations, not in assigning disease meaning to MUN itself.

PRECISION LIVESTOCK FARMING AND INTEGRATED DECISION SUPPORT

Sensors, Computer Vision, and Predictive Models

Precision livestock farming creates the technical infrastructure to combine milk composition, production, behavior, clinical records, and environmental measurements. Its potential contribution to sustainability and welfare has been widely discussed, but the biological validity of each sensor output and the translation of alerts into management decisions remain critical requirements (Lovarelli *et al.*, 2020; Kleen; Guatteo, 2023; Silva *et al.*, 2021).

Recent predictive studies illustrate how multimodal information can be used. Zhou *et al.* (2026) applied machine learning and SHapley Additive exPlanations to mastitis prediction using activity, rumination, milk yield, and milk electrical conductivity. Shahinfar *et al.* (2021) reviewed machine-learning approaches for lameness prediction.

Computer-vision approaches have also demonstrated the feasibility of extracting biologically relevant phenotypes from cattle images. Weber *et al.* (2020), for example, combined image-derived body measurements with regression and machine-learning algorithms to estimate body weight in Girolando cattle. Camera-based methods have also expanded toward more continuous and automated monitoring applications: Asim *et al.* (2026) applied deep learning to cattle activity monitoring, Yuan *et al.* (2026) reviewed computer-vision approaches to cattle behavior recognition, Fiorilla *et al.* (2026) developed a barn-wide monitoring framework under commercial robotic-milking conditions, and Tun *et al.* (2026) used depth images and deep learning for lameness detection.

Automated individual-animal identification represents another important component of longitudinal precision monitoring, and deep-learning-based computer-vision approaches have shown potential for recognizing individual cattle from facial information (Porto *et al.*, 2024).

These technologies demonstrate the feasibility of integrating heterogeneous data streams, but they also highlight limitations that are directly relevant to future MUN models. Differences among farms, cameras, housing systems, breeds, lighting, occlusion, diets, and disease prevalence can reduce generalizability. Therefore, predictive performance should be assessed with external validation and with explicit attention to whether adding MUN provides information beyond production and behavioral variables already available.

Proposed Integrative Framework

A practical interpretation can be organized into four complementary domains (Table 1). In this framework, MUN is positioned as a nutritional-metabolic sentinel rather than as an isolated diagnostic test. Its main contribution is to flag potential imbalance in nitrogen use; physiologic, behavioral, and clinical information then determines whether the signal is limited to nutrition or is accompanied by broader evidence of health or welfare disruption.

Table 1

Integrative framework for interpreting milk urea nitrogen with complementary dairy-cattle indicators

Domain	Examples of indicators	Information contributed	Interpretive role of MUN
Nutritional-metabolic	MUN; milk yield and components; dietary protein; fermentable energy	Protein-energy synchrony, nitrogen capture, urea recycling, nitrogen excretion	Direct: MUN is primarily interpreted in this domain
Physiologic-health	Cortisol; glucose; creatine kinase; acute-phase proteins; leukocyte profile	Metabolic adaptation, inflammation, tissue and endocrine responses	Contextual: supports investigation but does not convert MUN into a stress or disease marker
Behavioral	Rumination; feeding; lying; standing; activity; drinking	Early, nonspecific deviations in animal state	Contextual: temporal concurrence may strengthen the need for closer assessment
Clinical-welfare	Body condition; lameness; mastitis; clinical records; standardized pain measures	Clinical confirmation, welfare assessment, and risk stratification	Confirmatory context: determines whether an MUN deviation has broader clinical relevance

Source: Prepared from the reviewed literature (2026).

The proposed framework separates screening from diagnosis. A nutritional-metabolic

signal should first be checked against ration composition, milk production, and repeated MUN measurements. When the signal persists or is accompanied by behavioral or physiologic deviations, the animal or group can be prioritized for clinical evaluation. This sequential interpretation is compatible with precision-herd management because it uses low-burden variables to guide, rather than replace, targeted examination.

RESEARCH GAPS AND PRIORITIES

The major evidence gap is the scarcity of studies designed specifically to test whether MUN adds independent information to physiologic, behavioral, or welfare outcomes. Most available studies describe these domains separately. Longitudinal designs are therefore needed to determine temporal ordering and to distinguish associations driven by diet or production from those related to health.

Future studies should control, at minimum, for lactation stage, milk yield, parity, diet, farm, season or heat load, and repeated measurements within cows. They should also test whether relationships are linear, whether both low and high MUN values carry information, and whether the direction and magnitude of associations are consistent across production systems. Priority questions include:

a) Are persistent MUN deviations associated with changes in rumination, feeding, lying time, or activity after adjustment for diet and production?; b) Do MUN patterns contribute information beyond conventional metabolic, inflammatory, and leukocyte biomarkers when identifying cows with subclinical health disturbances?; c) Does adding MUN improve the discrimination, calibration, and clinical usefulness of predictive models based on production and sensor data?; d) Are proposed associations reproducible across breeds, housing systems, climates, and farms, and can they be externally validated?; e) Can integrated MUN-based monitoring improve nitrogen-use efficiency and herd-level decision-making without increasing false health or welfare alerts?

Answering these questions will require prospective cohorts with repeated measurements and independent validation datasets. Until such evidence is available, MUN should remain a nutritional-metabolic indicator whose health and welfare significance is established only by complementary data.

CONCLUSION

Milk urea nitrogen is a practical and widely available indicator of protein nutrition, urea metabolism, nitrogen excretion, and nitrogen-use efficiency in dairy cattle. Current evidence does not support interpreting it alone as a direct marker of stress, pain, disease, or animal welfare. Its broader value lies in contextual integration: persistent MUN deviations can identify nutritional-metabolic situations that merit interpretation alongside production records, blood biomarkers, behavior, environmental conditions, and clinical examination.

Precision livestock technologies make this integration increasingly feasible, but prospective and externally validated studies are still required to determine whether MUN adds meaningful predictive value for health and welfare monitoring. Accordingly, MUN is best viewed as a nutritional-metabolic sentinel within a multi-indicator decision-support framework, not as a stand-alone diagnostic biomarker.

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