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Review Article

A Review of Negative Energy Balance in Dairy Cattle Among Smallholder Farmers

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Abstract | Dairy farming's in Indonesia predominantly managed by smallholder farmers operating on a limited scale. Although their a critical role in the national milk supply, the productivity remains relativity low, primarily due to restricted feed resources and suboptimal management practices. One of the major challenges encountered is Negative Energy Balance (NEB), which is an energy deficit occuring in early lactation dairy cattle when energy demand for milk synthesis exceeds dietary energy intake. NEB triggers excessive mobilization of body fat, elevates blood β-hydroxybutyrate (BHB) concentrations, and triggers oxidative stress and hepatic dysfunction. These physiological disturbances result in decrease levels of Insulin-like Growth Factor-1 (IGF-1), estrogen, and prolactin hormones, which ultimately lead to reduced milk production, reproductive disorders, and an increased susceptibility to metabolic disorders. The prevalence of NEB among smallholder farms in Indonesia is notably high, largely influenced by environmental heat stress and limited access to quality forage. Effective prevention requires a comprehensive management strategy encompassing improved feeding practices, optimized calving management, and targeted nutritional supplementation. Supplementation with compounds such as lecithin, leucine, vitamin E, and selenium has been shown to enhance energy status, support metabolic function, and mitigate oxidative stress. Furthermore, farmer training in modern management techniques including precise feeding schedules aligned with lactation physiology is essential. Regular health monitoring, particularly BHB level assessment, facilitates early detection of NEB. The adoption of precision technologies, such as feeding activity sensors, can further enable real-time monitoring of intake patterns. In addition, policy interventions through subsidies or incentives are critical to strengthening energy resilience and overall health in smallholder dairy systems.

Keywords | Dairy cattle, Indonesian, Metabolism, Negative energy balance, Smallholder farmers

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INTRODUCTION

The dairy farming sector in Indonesia is predominantly characterized by smallholder operations, which constitute approximately 80% of the total farming population, with the remainder represented by industrial-scale farms (Widyobroto, 2024). Smallholder farms contribute the majority of national milk yield, typically maintaining only 2–5 dairy cattle per household (Fadillah *et al*., 2023). Despite their significant role in domestic milk supply, productivity remains relatively low, averaging 10 liters per cow per day or approximately 3,050 kg per lactation period (Christi *et al*., 2023). These figures highlight a substantial disparity when compared with the productive potential of Friesian Holstein (FH) cattle in their country of origin, where average yields reach 19.7–23 liters/head/day or up to 7,000 kg per lactation (Susanti *et al*., 2025). This disparity becomes even more pronounced when benchmarked against the average milk yields reported in other major dairy-producing countries, such as Ireland (5,620 kg/lactation), Australia (6,500–8,400 kg/lactation), as well as Finland, Sweden, and Japan, where production levels have surpassed 9,000 to 10,000 kg per lactation (Petrov *et al*., 2024).

Low milk production in Indonesian smallholder dairy farms is primarily attributed to limited capital, restricted access to high-quality forage, and insufficient land for forage cultivation (Jafri *et al*., 2024). Consequently, the nutritional requirements of dairy cattle are often unmet, reducing production efficiency and weakening the competitiveness of smallholder systems. During early lactation, energy demands increase substantially, and inadequate dietary energy intake can precipitate Negative Energy Balance (NEB) (Dai *et al*., 2023). NEB is a metabolic state characterized by energy expenditure exceeding dietary intake (Utamy *et al*., 2024). NEB occurs when energy intake fails to meet metabolic requirements, prompting mobilization of adipose tissue reserves into non-esterified fatty acids (NEFA) for Adenosine Triphosphate (ATP) synthesis and milk production (Martens, 2023; Swartz *et al*., 2021).

Persistent NEB can lead to clinical and subclinical ketosis, metabolic disorders, and reproductive dysfunction. These conditions manifest as reduced Body Condition Score (BCS), lower conception rates, prolonged days open, and increased incidence of repeat breeding (Siska and Anggryni, 2020; Meliana and Rohmawati, 2023). Additionally, oxidative stress associated with elevated metabolic activity may induce systemic inflammation, ovarian dysfunction, and alterations in gene expression (Mekuriaw, 2023; Wrzecińska *et al*., 2021).

A comprehensive understanding of NEB in smallholder dairy systems is essential for improving the productivity and reproductive performance of FH dairy cattle in Indonesia. Although NEB has been extensively discussed in the global literature, research focusing on smallholder dairy farms particularly those characterized by limited land resources and financial constraints in Indonesia remains extremely scarce. Therefore, this paper aims to systematically review NEB occurrence in smallholder farms and its implications for animal health and reproductive efficiency.

Negative energy balance incidence rate in several countries and their impact on dairy cattle

Negative Energy Balance is a common physiological condition in early lactation dairy cattle, characterized by elevated metabolic demands for milk synthesis that exceed energy intake from feed (Freitas *et al*., 2025; Vossebeld *et al*., 2022). A primary indicator of NEB is a reduction in body condition score (BCS), which reflects the status of body energy reserves (Singh and Bhakat, 2022). A decline in BCS of more than 0.5 points indicates intensive mobilization of adipose tissue to meet energy requirements (Triwutanon and Rukkwamsuk, 2021). This reduction not only compromises production performance but also impairs immune function, elevates the risk of reproductive disorders, and induces alterations in metabolite and hormonal profiles that negatively affect fertility (Vidu *et al*., 2025). BCS assessment, based on visual appraisal and palpation, is widely employed to evaluate the health and energy status of dairy cattle (Praveen *et al*., 2024). A decrease in BCS exceeding 1.0 points within the first month of lactation is associated with prolonged ovulation intervals, reduced conception rates, and increased incidence of health complications (Kamali and Ahmadi, 2022; Manríquez *et al*., 2021). Furthermore, cattle experiencing excessive BCS loss exhibit impaired embryonic development during the first week following artificial insemination.

The incidence of NEB in dairy cattle in Indonesia, as reflected by the prevalence of subclinical ketosis, ranges from 7.5% to 14% during the early lactation period. This prevalence indicates that a proportion of dairy cattle experience metabolic disorders strongly associated with energy deficiency (Saradhi *et al*., 2024). A decline in BCS serves as a critical indicator for detecting NEB, with the optimal BCS for Friesian Holstein (FH) dairy cattle ranging between 2.5 and 3.0 (Montiel-Olguin *et al*., 2019). Dairy cattle exhibiting high BCS (<3,5) are more susceptible to subclinical ketosis due to reduced feed intake, which promotes body fat mobilization and elevates blood ketone concentrations (Melendez *et al*., 2025). A field study conducted on smallholder farms in the Lembang region of West Java revealed that 60% of FH dairy cattle experienced a BCS decline of more than 1.0 point within the first 30 days of lactation, indicating the presence of subclinical NEB. Consequently, 45% of these cattle exhibited reproductive disorders, including repeat breeding and prolonged days open. In addition, daily milk yield decreased markedly from 14 liters to 9 liters per cow per day, underscoring the significant impact of NEB on both reproductive performance and productivity.

Furthermore, approximately 40–55% of dairy cattle in Indonesia experience reproductive disorders associated with decreased BCS (Nurhaliza and Humaidah, 2023), indirectly reflecting the high prevalence of NEB in the field. Globally, blood β-hydroxybutyrate (BHB) concentrations in early lactation dairy cattle range from 0.7 to 1.5 mmol/L. Countries such as Argentina (0.9 mmol/L), Australia (0.7 mmol/L), Brazil (0.7 mmol/L), Chile (0.8 mmol/L), China (1.2 mmol/L), Colombia (0.7 mmol/L), Mexico (0.8 mmol/L), Russia (0.7 mmol/L), South Africa (0.9 mmol/L), and Ukraine (1.5 mmol/L) (Brunner *et al*., 2019). In Asia, including Indonesia, BHB levels tend to be higher (≥1.0 mmol/L), indicating that dairy cows in tropical regions are more susceptible to NEB (Utamy *et al*., 2025).

Metabolically, the most widely used biomarker for determining NEB status in dairy cattle is blood BHB concentration (Kaniamuthan *et al*., 2025). BHB is considered reliable because of its stability in circulation. Elevated BHB levels indicate the severity of NEB, with concentrations between 0.59 and 0.97 mmol/L classified as mild NEB (Chaput and Sirard, 2020), while levels ≥1.1 mmol/L are indicative of severe NEB. High BHB concentrations are strongly correlated with oxidative stress and hepatocellular apoptosis, which impair liver function and lead to ketosis (Grzybowska *et al*., 2025). Ketosis in dairy cattle results in substantial economic losses due to reduced milk yield, impaired reproductive performance, hormonal imbalances, increased culling rates, and, in severe cases, mortality (Soest *et al*., 2024). A field study on smallholder farms in the United States, based on blood analysis of FH cattle, reported an average BHB level of 1.3 mmol/L, indicating severe NEB and ketosis. The estimated annual cost per ketosis case ranges from USD 129 to 289, equivalent to approximately IDR 2,153,667–4,824,883. These costs primarily arise from veterinary and treatment expenses per animal, future reproductive performance losses (34%), mortality losses (26%), and reductions in expected milk productivity (26%) (Lei and Simões, 2021).

In addition to a reduction in BCS, cattle experiencing NEB also exhibit a decline in milk productivity. Milk yield is a critical determinant of dairy farm profitability and overall production efficiency. NEB is associated with decreased dry matter intake (DMI) and reduced feed efficiency, which negatively affect milk output and alter milk composition, including fat, protein, lactose, and total solids (Martens, 2023; Wang *et al*., 2022). Furthermore, insufficient energy intake limits the availability of amino acids required for the synthesis of milk components, thereby compromising milk quality (Kim and Lee, 2021).

Indonesia's hot and humid tropical climate, with temperatures ranging from 26–34°C and relative humidity between 52–81%, deviates substantially from the optimal conditions for FH dairy cattle, which are approximately 18.3°C and 55% humidity (Utamy *et al*., 2025). Heat stress under these conditions can reduce feed conversion efficiency by up to 50%, markedly decrease dry matter intake (DMI), and increase the risk of clinical NEB (Kim *et al*., 2022). During the summer, environmental temperatures may exceed 38.4°C, coinciding with calving rates of up to 70%, which indicates a high proportion of cattle in early lactation during this period. Limited forage availability combined with severe heat stress exacerbates NEB incidence, negatively affecting productivity and health, and further signaling the occurrence of ketosis in smallholder dairy farms (Bercea *et al*., 2020).

Increased growth hormone (GH) and decreased insulin concentrations lead to a reduction in insulin-like growth factor-1 (IGF-1) levels, which promotes lipolysis and non-esterified fatty acid (NEFA) release, thereby reducing glucose uptake. A decline in IGF-1 is considered a key indicator of NEB. Cattle experiencing NEB exhibit IGF-1 concentrations ranging from 27.18 ng/mL in mild NEB cases to approximately 11 ng/mL in severe NEB cases (Qiao *et al*., 2024; Fenwick *et al*., 2008). Reduced IGF-1 levels are associated with decreased estrogen and prolactin concentrations, which prolong postpartum recovery, particularly ovarian activity (Zhao *et al*., 2021; Dar *et al*., 2021). These hormonal changes contribute to reproductive disorders, inhibit estrous cycles, lower conception rates, and increase the incidence of repeat breeding (Sitaresmi *et al*., 2023; Amin *et al*., 2023; Jeong and Kim, 2022). Furthermore, hormonal suppression compromises immune function, increasing susceptibility to infectious diseases such as mastitis, metritis, and retained placenta (Raj *et al*., 2025). Collectively, NEB represents a complex physiological condition that impairs both production and reproductive performance through interconnected metabolic and endocrine mechanisms.

Table 1 shows a comparison of NEB with Positive Energy Balance (PEB) dairy cattle based on references, while Figure 1. Shows the illustrations of the effects of NEB on dairy cattle.

Integrated strategis for effective management of negative energy balance in dairy cattle

Integrated strategies for effective management of NEB in dairy cattle rely on a synergistic approach that integrates feeding, calving management, maintenance practices, and targeted nutrition. This comprehensive strategy aims not only to enhance energy intake and prevent excessive mobilization of body fat but also to maintain metabolic homeostasis, support reproductive health, and ensure sustainable milk production and quality.

Feed management

Feed management during early lactation is a critical component in mitigating NEB, as energy requirements increase substantially while feed intake capacity remains suboptimal (Méndez *et al*., 2024). During the transition period approximately three weeks before and after calving the primary objective is to maximize DMI through the provision of high-quality feed with balanced nutrient composition (Caixeta and Omontese, 2021). A strategic combination of high-quality forage and nutrient-dense concentrates can help meet the physiological demands of dairy cattle, thereby reducing the risk of metabolic disorders such as ketosis (Vithalrao *et al*., 2025; Wadal *et al*., 2023).

Feeding energy-restricted diets during the dry period has demonstrated positive effects on metabolic adaptation and reduced the incidence of mild NEB postpartum without compromising milk yield (Lei and Simões, 2021). Optimizing feed quality, texture, and aroma is essential for maintaining palatability and consistent intake, particularly under conditions of physiological and hormonal stress caused by decreased progesterone, elevated corticosteroids, and environmental heat stress (Lovarelli *et al*., 2024).

Feeding frequency and ration size also influence metabolic homeostasis (Mota *et al*., 2022). Dairy cattle fed twice or more daily exhibit less feed sorting compared to those fed once per day. Therefore, feed management should be complemented by regular monitoring of BCS and blood metabolites as indicators of energy status (Martens, 2023). Dynamic feed adjustments based on lactation stage and body condition are strongly recommended to prevent excessive deterioration of body reserves.

Nutritional supplementation represents a vital component of NEB management, particularly during the transition and early lactation phases when energy demands peak (Kour *et al*., 2024). The primary objectives of supplementation are to improve energy balance, support metabolic function, and prevent physiological disorders that compromise productivity and health (Sammad *et al*., 2022).

Energy supplementation

Providing additional energy sources such as propylene glycol, glucose, and rumen-protected fat can enhance energy availability without disrupting rumen fermentation (Du *et al*., 2023). Propylene glycol is particularly effective in reducing blood BHB concentrations and preventing subclinical ketosis (Song *et al*., 2025). This supplement is typically administered orally or incorporated into feed for 7–14 days postpartum (Zhang *et al*., 2022).

Protein supplementation

High-quality protein supplementation, especially rumen undegradable protein (RUP), plays a critical role in reducing body protein catabolism, supplying essential amino acids for milk synthesis and tissue recovery, and improving energy utilization efficiency (Thakur *et al*., 2024). Adequate levels of methionine and lysine enhance energy conversion into milk components (Wróbel *et al*., 2025), indirectly improving energy balance. Protein supplementation also supports immune and reproductive functions (Xiao *et al*., 2025). Conversely, protein deficiency can impair immune response and exacerbate postpartum reproductive disorders, which often coincide with NEB (Sklyarov *et al*., 2023). Energy supplementation without adequate protein may lead to metabolic imbalances, such as elevated blood nitrogen or reduced rumen microbial efficiency (Desta, 2024).

Essential amino acid supplementation

Leucine is an essential amino acid that plays a pivotal role in protein synthesis and the regulation of energy metabolism (Rehman *et al*., 2023). Supplementation with leucine has been shown to enhance energy utilization efficiency, accelerate tissue recovery, and support milk yield (Elsaadawy *et al*., 2022). Alongside leucine, methionine, and lysine are critical for milk component synthesis and reproductive function (Gilbreath *et al*., 2021). Notably, leucine supplementation has successfully reduced blood BHB concentrations to 0.68–0.72 mmol/L within three weeks postpartum, while progressively improving body condition score (BCS) and milk yield (Elsaadawy *et al*., 2022).

Vitamin and mineral supplementation

Vitamin E and selenium act as potent antioxidants that protect cellular structures from oxidative stress associated with increased metabolic activity during NEB (Xiao *et al*., 2021). Deficiencies in these micronutrients can compromise immune function (Chen *et al*., 2023) and elevate the risk of metabolic disorders such as mastitis and metritis (Khan *et al*., 2024). Additionally, calcium and magnesium are essential for supporting muscle contraction and nerve function during and after parturition (Ibrahim and Kirman, 2021).

Choline and lecithin supplementation

Choline and lecithin play essential roles in lipid metabolism and hepatic function (Araee and Ghoorchi, 2023). Supplementation with rumen-protected choline has been shown to reduce hepatic fat accumulation and enhance lipid metabolic efficiency (Huang *et al*., 2023). Similarly, lecithin supports lipid transport and improves the overall metabolic profile of dairy cattle during periods of NEB (Hu *et al*., 2025).

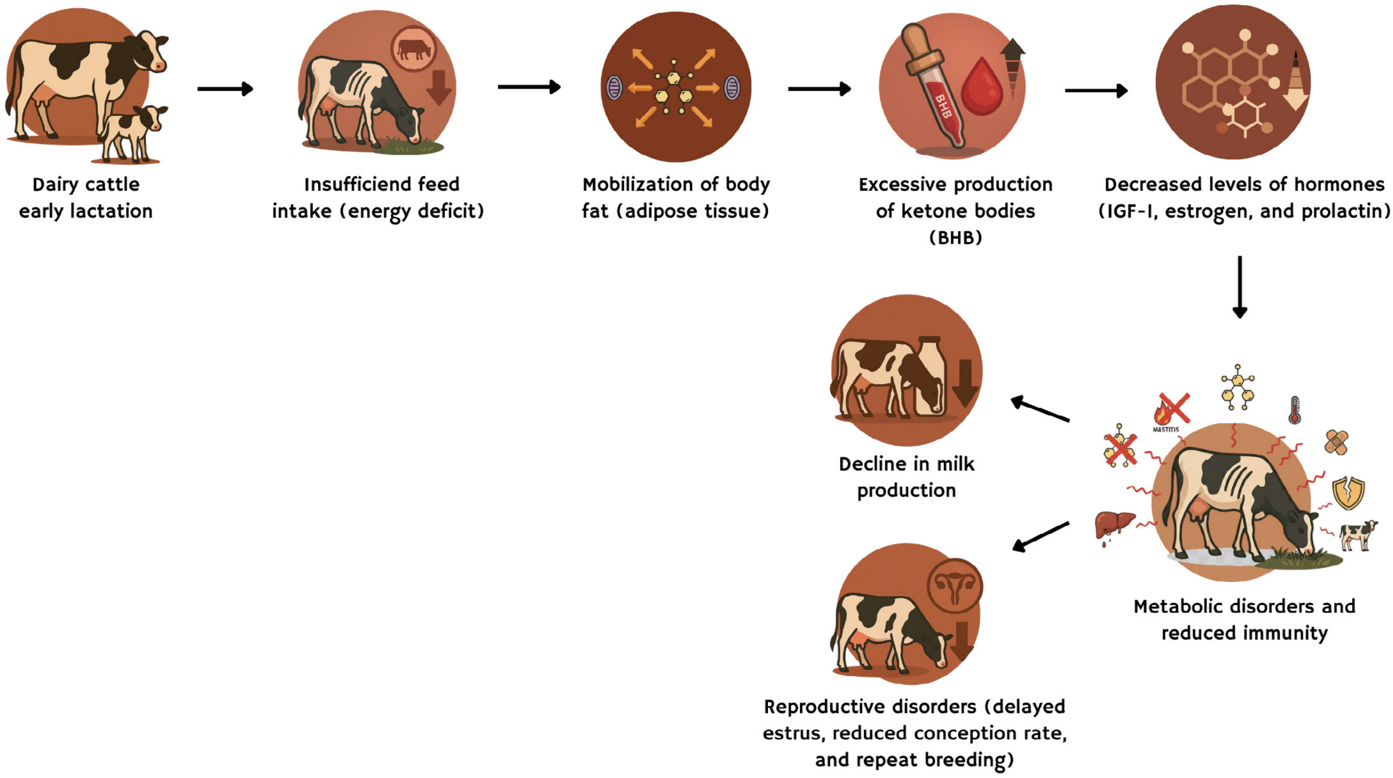

Figure 1: Effect of NEB on dairy cattle.

Table 1: Comparison of NEB with PEB in dairy cattle.

Indicator	NEB	PEB	Reference
BCS	2.6	3.5	Triwutanon and Rukkwamsuk, 2021
BHB (mg/dL)	7.8	6.0	Hod *et al.*, 2023
IGF-1 (ng/mL)	27.18	78.04	Kupiainen, 2021
NEFA (mmol/L)	0.85	0.55	Wang *et al.*, 2022
Glucose (mg/dL)	57.5	62.9	Hod *et al.*, 2023

Negative Energy Balance (NEB); and Positive Energy Balance (PEB). BCS= Body Condition Score; BHB= Beta-Hydroxybutyrate; IGF-1= Insulin-like Growth Factor 1; NEFA= Non-Esterified Fatty Acids.

Probiotic and prebiotic supplementation

Probiotics such as *Saccharomyces cerevisiae* and *Lactobacillus* spp. Enhance rumen microbial activity (Lambo *et al.*, 2024); improve fiber fermentation (Elghandour and Hafsa, 2024); and increase DMI (Niknia *et al.*, 2025). Prebiotics, including *Mannan-oligosaccharides* (MOS), contribute to gastrointestinal health and strengthen immune function (Grossi *et al.*, 2021).

Grouping based on needs

Supplementation strategies should be tailored to the lactation phase, body condition, and metabolic history of the cow (Taufarelli *et al.*, 2024). Grouping cattle based on BCS and reproductive status enables more targeted nutritional interventions, thereby effectively minimizing the impact of NEB (Vidu *et al.*, 2025).

Table 2 provides a summary of the various types of nutritional supplementation commonly applied in NEB management for dairy cattle, including their primary objectives and examples of frequently used supplements.

Calving management

Birth management is a critical phase that significantly influences the health status and lactation performance of dairy cattle. Proper calving planning aims to minimize physiological stress during parturition, accelerate postpartum recovery, and enhance feed intake after calving (Galadima, 2024). Comfortable housing conditions, strict sanitation, and appropriate calving assistance reduce the risk of complications such as dystocia, which can exacerbate energy deficits (Okoth *et al.*, 2024).

Adequate nutritional intake and hydration before and during calving are essential, including sufficient mineral and energy supply to support optimal parturition (Cargile and Tracy, 2021). Nutritional interventions during the periparturient period have been shown to improve milk yield and reduce the prevalence of NEB-related metabolic disorders such as ketosis (Kotsampasi *et al.*, 2024; Khan *et al.*, 2024).

Intensive monitoring during and after calving, including clinical assessment of NEB indicators and BCS measurement, is crucial for early intervention. Managing cattle to calve at an optimal BCS of 3.0–3.5 minimizes NEB risk (Vidu *et al.*, 2025). Additionally, technologies

Table 2: Types of nutritional supplementation used in NEB management in dairy cattle, along with their main purposes and examples of supplements.

Types of supplements	Main objective	Example of supplements
Energy	Increasing energy availability, preventing ketosis, and supporting milk yield[(a)]	Propylene glycol, glucose, protected fats[(b)]
Protein	Provides nitrogen and amino acids for protein synthesis, tissue growth and repair[(c)]	Rumen undegradable protein (RUP), fish meal, protected soybean meal[(d)]
Essential Amino Acids	Provides key limiting amino acids, particularly methionine and lysine, which escape rumen degradation for optimization of energy metabolism and milk yield and components (milk proteins)[(e)]	Leucine, Methionine, Lysine
Vitamin and Mineral	Meets increased needs for fat-soluble vitamins, minerals as antioxidants, supports immune function and muscle function[(g)]	Vitamin E, Selenium, Calcium, and Magnesium[(h)]
Colin and Lecithin	Supports fat metabolism and liver function[(i)]	Rumen-protected choline chloride and Lecithin[(j)]
Probiotic and Prebiotic	Improves rumen fermentation and digestive health[(k)]	Live yeast (Saccharomyces cerevisiae), (Lactobacillus spp) and Mannan-oligosaccharides (MOS)[(l)]
Grouping	Improving palatability strategies based on lactation phase, body condition, and metabolic history [(m)]	Based on BCS, Reproductive Status[(n)]

(a) Sycheva *et al.*, 2021; (b) Zhang *et al.*, 2025; (c) Benn, 2023; (d) Mohammadkhani *et al.*, 2025; (e) Benoit and Whitehouse, 2025; (f) Kim and lee, 2021; (g) Andres *et al.*, 2024; (h) Mitra *et al.*, 2022; (i) Obeid *et al.*, 2024; (j) Wang *et al.*, 2021; (k) Chowdhury *et al.*, 2025; (l) Zeeshan *et al.*, 2023; (m) Souza *et al.*, 2025; (n) Antanaitis *et al.*, 2022.

such as blood BHB testing enable rapid detection of ketosis, allowing timely administration of energy supplements or corrective measures. Effective calving management accelerates the onset of active lactation and supports overall productivity and health in dairy cattle (Singh, 2021).

Maintenance management

Optimal maintenance management is essential for sustaining stable production performance in dairy cattle, particularly during the transition period and early lactation when the risk of NEB is highest. Effective maintenance strategies include maximizing feed intake, implementing routine health monitoring, and managing the housing environment to ensure thermal comfort (Triwutanon and Rukkwamsuk, 2021).

Dairy cattle experiencing NEB typically exhibit reduced immune responsiveness, making them more susceptible to infections and metabolic disorders such as mastitis and metritis (Mezzeti *et al.*, 2014; Dai *et al.*, 2023). Therefore, strict barn sanitation and robust biosecurity measures are critical, especially for early lactation cattle, to prevent disease complications that exacerbate NEB.

Environmental comfort plays a pivotal role in mitigating heat stress, a major contributor to NEB. The optimal temperature range for dairy cattle is 15–25°C with relative humidity between 50–78% (Oliveira *et al.*, 2025). Implementing water-based cooling systems and efficient cross-ventilation can reduce barn microclimate temperatures and improve air circulation, thereby supporting thermal comfort and maintaining feed intake at optimal levels (Asmarasari *et al.*, 2023).

Adequate water availability is equally important for hydration, thermoregulation, and metabolic function. Stress management strategies should include temperature regulation, proper ventilation, and provision of high-quality feed to stimulate appetite even under hormonal imbalances caused by stress (Triwutanon and Rukkwamsuk, 2021). Additionally, supplementation with antioxidants such as vitamin E and selenium, as well as bioactive compounds, can help mitigate the adverse effects of stress on metabolism and immune function.

The role of leucine feed supplements in reducing negative energy balance

Leucine is an essential amino acid that plays a central role in regulating energy metabolism and protein synthesis, particularly in dairy cattle experiencing NEB. Leucine supplementation activates the mammalian target of rapamycin complex 1 (mTORC1) signaling pathway, which enhances muscle protein synthesis and reduces proteolysis, thereby helping to preserve muscle mass during early lactation (Kim and Lee, 2021; Melnik, 2012).

Incorporating leucine into the diet not only improves the efficiency of other amino acid utilization but also optimizes overall energy metabolism. Leucine contributes to hepatic function by promoting gluconeogenesis and lipid metabolism, while reducing the accumulation of ketone bodies such as BHB, which typically increases in cattle with NEB (Wang *et al*., 2022).

Moreover, leucine plays a role in strengthening immune responses, enabling cattle to better cope with physiological stress and maintain productivity. Recent studies indicate that leucine supplementation during early lactation enhances milk yield and improves the milk metabolomic profile, including increased milk protein content (Gallagher *et al*., 2024; Wang *et al*., 2022).

Thus, leucine supplementation represents a precision nutrition strategy that not only supports energy recovery and metabolic stability but also improves production performance and overall health during the critical NEB period.

CONCULUSION

Negative energy balance is a major contributor to reduced productivity in dairy cattle, particularly during early lactation when energy demands rise sharply but are not met by adequate feed intake. This imbalance results in elevated blood BHB concentrations, decreased BCS, metabolic disturbances, and reductions in key hormones such as IGF-1, estrogen, and prolactin, all of which negatively affect milk yield and reproductive performance. The high prevalence of NEB underscores the need for rigorous nutritional and management intergration. Indicators such as declining BCS, increased BHB levels, and reduced milk yield should serve as benchmarks for assessing metabolic status in dairy cattle. The extensive impact of NEB from health disorders to impaired reproductive efficiency necessitates comprehensive management strategies. Effective NEB mitigation can be achieved through high-quality feed management, optimal calving practices, and maintenance of housing environments that promote thermal comfort. Nutritional supplementation, including essential amino acids such as leucine, has demonstrated benefits in improving energy balance, enhancing nutrient utilization efficiency, and supporting hepatic and immune functions. Furthermore, optimal environmental management including control of temperature, humidity, ventilation, and water availability plays a critical role in reducing heat stress, a key factor exacerbating NEB. Integrating nutritional strategies with environmental stress control offers a sustainable approach to improving productivity and health in dairy cattle during the critical early lactation period.

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NOVELTY STATEMENT

While Negative Energy Balance (NEB) in high-producing dairy cattle has been extensively documented globally, its specific occurrence, risk factors, and practical mitigation strategies within smallholder farming systems in tropical regions-particularly Indonesia-remain critical research gaps. This review fills this vacuum by systematically evaluating the metabolic, physiological, and hormonal impacts of NEB under smallholder constraints, such as limited capital, land scarcity for high-quality forage, and heat stress. Furthermore, it highlights localized, cost-effective prevention strategies, including precision feeding schedules and the incorporation of fortified local forages, offering a tailored framework to enhance smallholder dairy resilience and productivity.

AUTHOR'S CONTRIBUTION

Azisah Nurfadilah: Conceptualization, methodology, formal analysis, data curation, writing original draft preparation. Renny Fatmyah Utamy: Supervision, conceptualization, writing review and editing, validation, corresponding author. Muhammad Ihsan A. Dagong: Supervision, validation, visualization. Ambo Ako: Supervision, investigation, resources. Irmayanti, Zyahrul Ramadan, Ikran, Nur Fajri Muhlis: Data collection, literature screening, software support, and critical revision of the manuscript. All authors have read and agreed to the published version of the manuscript.

Generative AI and AI assisted technology statement

The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest

The authors have declared no conflict of interest.

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