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Effect of feed and manure management on nitrogen footprints of commercial dairy farms: A survey study of Central Punjab

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Abstract

Dairy farming is vital for global food security and economic stability. However, inefficient nitrogen (N) utilization in dairy farms contributes to ammonia volatilization, nitrate leaching, and greenhouse gas emissions, posing serious environmental challenges. Although developed countries have made substantial investment in nitrogen management, many developing regions of the world, including Pakistan, are still using high-protein feed coupled with manure management practices with substantial nitrogen losses and overall low nitrogen use efficiency (NUE). Nitrogen sources, utilization, and excretion in Punjab commercial dairy farms are subject to strong influences from both the feed composition and the manure management employed in these systems. Farm surveys were complemented by direct observations on the 15 commercial dairy farms using a mixed-methods approach and feed and manure samples were collected for analysis. Pearson's correlation and regression model were used to assess relationships between nitrogen intake, excretion, and manure retention. Results revealed a bimodal herd size distribution, with most farms operating within 175–225 animals. A strong correlation (r = 0.87) was observed between dry matter intake (DMI) and manure generation. Lactating cows had the highest DMI (23.5 kg day^{-1}) with efficient nitrogen utilization, while calves exhibited the lowest nitrogen efficiency. Flush Systems had the highest nitrogen losses (3.8–5.5 g kg^{-1}, $p < 0.05$) due to higher ammonia volatilization and nitrogen runoff, whereas slatted floor and drylot systems retained the most nitrogen (>12 g kg^{-1}) by minimizing surface exposure and volatilization. These findings emphasize the urgent need for precision feeding, improved manure management, and policy-driven interventions.

Keywords: Nitrogen footprints, dairy farming, Pakistan, environmental sustainability

Introduction

Dairy farming is a fundamental component of Pakistan's agricultural economy, particularly in Punjab, which serves as the country's leading milk-producing region. The livestock sector contributes 61.89% of the agricultural GDP and employs approximately 30–35 million people in rural areas. With a 3.2% increase in the gross value of domestic milk between 2019 and 2020, the demand for dairy products is expected to rise further due to population growth and increasing per capita consumption (Rojas-Downing *et al*., 2017; Saleem *et al.*, 2023). However, the expansion of commercial dairy farms has raised concerns about nitrogen (N) utilization efficiency and environmental sustainability. Inefficient nitrogen use in dairy production contributes to nitrogen losses through excretion, volatilization, and leaching, leading to soil degradation, groundwater contamination, and greenhouse gas emissions.

Nitrogen sources and sinks in commercial dairy farms are primarily influenced by feeding practices and manure management strategies. Feeding strategies, particularly the choice of silage types (e.g., red clover, alfalfa, maize, and grass), play a crucial role in nitrogen metabolism, utilization efficiency, and excretion patterns in dairy cows. Studies suggest that optimizing dietary crude protein (CP) levels and feed composition for cattle feed (wanda/concentrate) can enhance nitrogen use efficiency (NUE), thereby reducing nitrogen wastage and improving milk production (Leduc *et al.*, 2023). Furthermore, manure management strategies like housing, flooring, and waste disposal affect nitrogen retention and losses. Ammonia emissions and nutrient runoff from poor manure handling increase dairy farms' nitrogen footprint (Fang *et al.*, 2020).

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In order to reduce environmental impacts, developed countries use advanced nitrogen management systems (Munidasa *et al.*, 2021). Many dairy farms in developing countries like Punjab, Pakistan, use conventional feeding regimes and improper manure disposal, resulting in high nitrogen losses. It has seen a more than ten-fold increase in nitrogen input from 408 $GgNyr^{-1}$ to 4636 $GgNyr^{-1}$ between 1961 and 2013. The inefficient use of nitrogen in dairy farming contributes to nitrogen losses, with surplus nitrogen increasing from 171 $GgNyr^{-1}$ to 3581 $GgNyr^{-1}$ over the same period, emphasizing the need to solve nitrogen inefficiencies (Bougouin *et al.*, 2022; Raza *et al.*, 2022). Key challenges include limited pasture availability, over-reliance on high-protein diets, inadequate manure treatment systems, and a lack of awareness among farmers regarding sustainable nitrogen management practices. It was hypothesised that inefficient nitrogen use in commercial dairy farms in Punjab is primarily driven by suboptimal feeding practices and inadequate manure management, leading to significant nitrogen losses and increased environmental burden.

The objective of this study was to quantify nitrogen sources and sinks of commercial dairy farms in Punjab, Pakistan along with the consideration of feed composition and manure management methods as key drivers of nitrogen footprints. In this study, a survey was carried out in the localized area of central Punjab to assess the current trends of nitrogen use practices, inefficiencies, and recommend local solutions for management of nitrogen. These data-driven insights were useful for Pakistani dairy farmers, policymakers, and researchers to facilitate the adoption of sustainable and ecologically friendly dairy production practices.

Materials and Methods

Study area

Punjab is a major dairy producer in Pakistan, where this study was undertaken. In Samundari, Deputywala, Tandlianwala, Gojra, Jhang, Sahiwal, and Khidarwala, fifteen commercial dairy farms were studied. The management approaches and dairy farming popularity of these localities determined their selection. Through feeding and waste management, the study assessed the nitrogen (N) footprint.

Study design

The study used a mixed-methods research design to combine qualitative and quantitative approaches which allowed for an in-depth study. The method incorporated use of surveys, direct observation and laboratory analysis of feeds and feces for nitrogen. The present study was able to assess nitrogen utilization efficiency (NUE) in commercial dairy farms as the analysis incorporates multiple data sources.

Survey design

A structured survey was conducted through face-to-face interviews with dairy farmers to collect data on herd size, feeding regimes, manure management practices, and nitrogen utilization awareness. The survey instrument consisted of closed-ended and open-ended questions to capture both quantitative and qualitative insights (Jackson *et al.*, 2022).

Research instrument

A semi-structured questionnaire was designed based on existing literature and expert consultations (Pandey and Pandey, 2015). The questionnaire covered:

a) **Farm demographics** (size, number of animals, breed composition)

b) **Feeding practices** (feed type, crude protein content, feed intake)

c) **Manure management strategies** (storage, disposal, application techniques)

Quantitative data collection

Quantitative data were collected primarily through structured interviews and direct observations. Since a significant proportion of respondents were semi-literate, interviews ensured accurate and consistent data collection (Phellas *et al.*, 2011). Proximate nitrogen (N) analysis of feed and feces samples was also conducted to quantify nitrogen input and output in dairy farms (Lavery and Ferris, 2021). Feces samples were collected from both fresh droppings and stored manure from the storage site for analysis.

Qualitative data collection

Complementary qualitative insights were collected to provide a more comprehensive view of the challenges of nitrogen efficiency (Aschbrenner *et al.*, 2022). Through open-ended questions and field observations, farmers reported their perceptions related to feed composition, manure handling, and environmental concerns. That approach allowed for more information on real-world limitations in N management.

Proximate nitrogen (N) analysis of feed and feces

To determine nitrogen flow within the dairy system, samples of common feed types and feces were collected from each surveyed farm. The Kjeldahl method was employed for nitrogen quantification (Lavery and Ferris, 2021).

Nitrogen analysis procedure

A one g finely ground feed or feces sample was placed in a crucible. A digestion mixture containing potassium sulfate (100 g), copper sulfate (5 g), and ferric sulfate (5 g) was added with 25–30 mL of sulfuric acid (H_2SO_4), and then sample was digested at 420°C for 1.5 hours until a clear light-green solution appeared. The digest was diluted to 250 mL with deionized water in a volumetric flask.In the distillation unit a 10 mL of the digested solution was transferred to a Kjeldahl distillation apparatus with 10 mL of 40% sodium hydroxide (NaOH) was added to release ammonia. The ammonia vapors were trapped in a 4% boric acid solution until the boric acid turned colorless. The colorless boric acid solution was titrated with N/10 sulfuric acid (H_2SO_4) until the original boric acid color reappeared. The volume of acid used was recorded for nitrogen calculation.

Nitrogen Calculation

% of Nitrogen = Reading of N/10 vol. used× factor × vol. used for dilution × 100 / Sample in g × prepared sample in mL

Data analysis

All collected data were analyzed using R-software. Descriptive statistics were applied to evaluate the demographic characteristics of dairy farms. Bivariate correlation analysis was conducted to examine the relationship between nitrogen inputs (feed composition) and nitrogen outputs (fecal and urinary excretion). Pearson's correlation coefficient (r) was used to assess the strength and direction of associations. A p-value < 0.05 was considered statistically significant, indicating a meaningful relationship between variables.

Results

Herd size distribution across dairy farms

The investigation of dairy farms classified by herd size (Figure 1) reveals important variance in the sizes of these farms. The highest density of farms is noted in the herd size between 175–225 animals, pointing to that a significant number of farms function at this level, likely because of a favourable equilibrium between productivity and financial outcomes. A secondary, less prominent peak is noticed within the 50–100 animal range, demonstrating the existence of smaller-scale farms that most likely concentrate on serving localised markets. There are relatively few farms that keep very large herd sizes, specifically those exceeding 300 animals, likely because of the significant practical and financial challenges associated with managing such extensive operations. The overall distribution illustrates the variety of dairy farm sizes, illustrating that the industry includes both small-scale and medium-to-large scale operations, each addressing distinct market demands and production strategies. This analysis offers a detailed examination of herd size preferences in the dairy farming sector, focussing on the necessity for targeted support and resources that meet to farms of different scales.

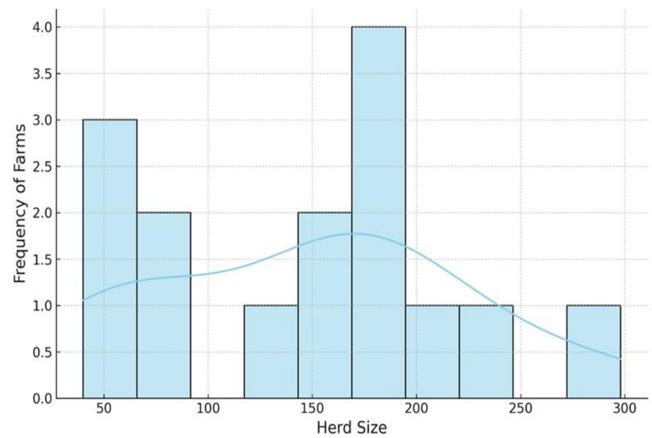

Figure 1. The distribution of dairy farms by herd size, indicating two significant peaks: 50–100 animals and 175–225 animals. This bimodal pattern displays a mix of small- and medium-to-large farms

Qualitative analysis of cattle parameters

The comprehensive analysis of cattle parameters reveals distinct patterns across different cattle categories, Figure 2 (A) illustrates the normalized values of body weight, dry matter intake, and manure generation across lactating cows, dry cows, heifers, and calves, with actual values annotated for precise reference. This visualization demonstrates the proportional relationships between these parameters, highlighting how lactating cows maintain the highest dry matter intake (23.5 kg d^{-1}) despite not having the highest body weight, which is observed in dry cows (612.5 kg). Figure 2 (B) presents the correlation matrix between the three key parameters, revealing a strong positive correlation ($r = 0.87$) between dry matter intake and manure generation, suggesting that feed consumption is a primary determinant of manure output. Additionally, a substantial correlation ($r = 0.94$) exists

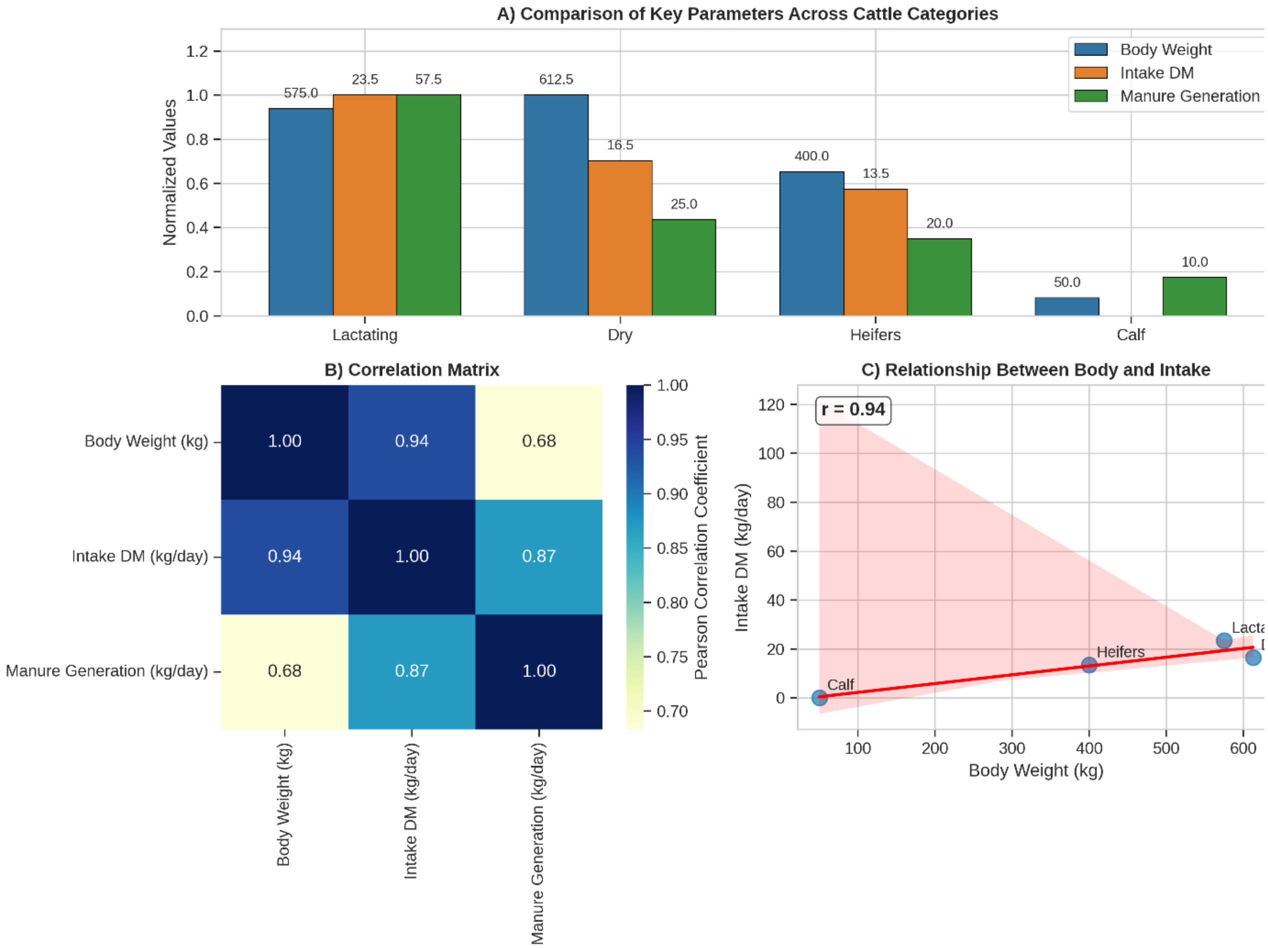

Figure 2. Analysis of survey data on cattle parameters. (A) Displays normalized values for direct comparison across cattle categories. (B) Presents the correlation matrix between key parameters, highlighting interrelationships. (C) Illustrates the correlation between body weight and dry matter intake, demonstrating their relationship across different cattle groups

between body weight and dry matter intake, while body weight and manure generation show a moderate correlation (r = 0.68). Figure 2 (C) further examines the strongest relationship between dry matter intake and body weight through regression analysis by animal category, visually confirming that lactating and dry cows had more weight so, they had more dry matter intake.

Nitrogen intake and excretion by category

An analysis was performed on the relationship between nitrogen intake and nitrogen excretion across four distinct animal types: lactating cows, dry cows, heifers, and calves. A regression analysis was performed to determine the changes in nitrogen excretion as an indicator of different nitrogen intake levels across each category. The findings are shown in figure 3, exhibiting unique regression lines along with the corresponding equations that highlight the particular relationship for each category.

In the case of lactating cows (blue line, y=0.447+0.102x), the slope of 0.102 implies a relatively weak positive correlation between nitrogen intake and excretion. It also suggests that with an increase in nitrogen intake, nitrogen excretion expands gradually, showing the effective utilization of nitrogen for milk production. Lactating cows requires increased nitrogen to meet the requirements of lactation; however, a significant portion of the intake is allocated to milk protein synthesis, leading to

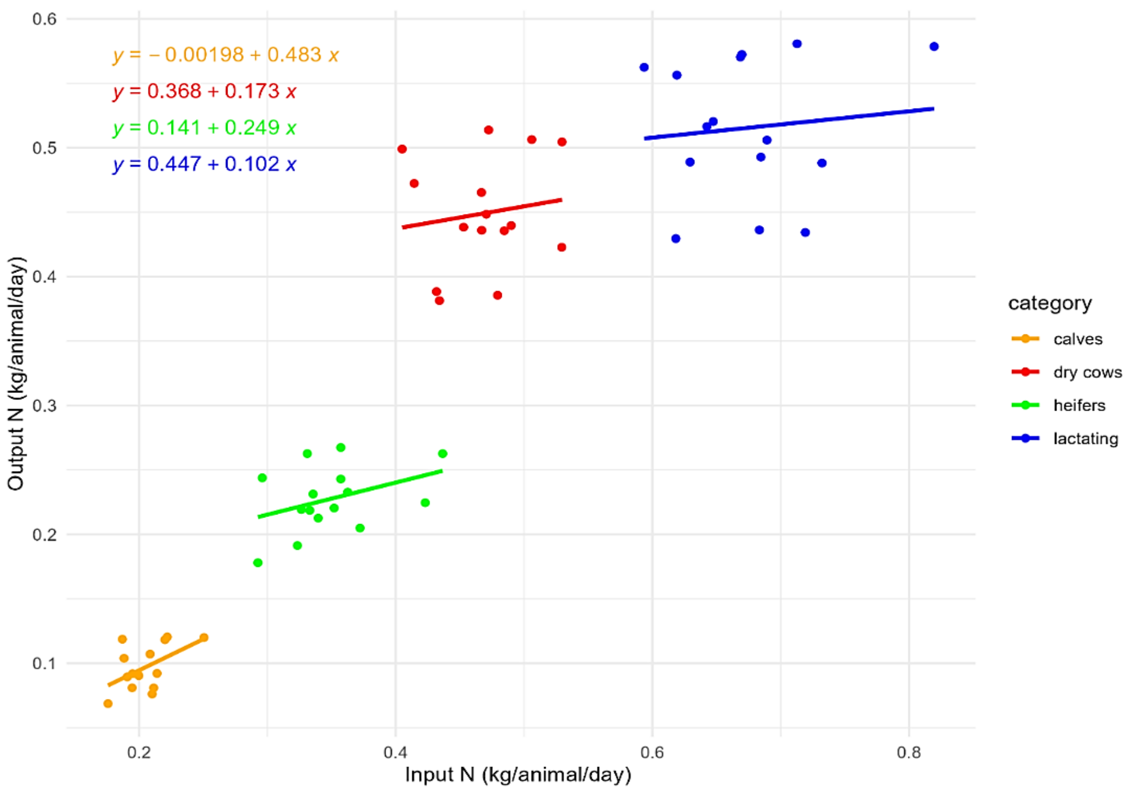

Figure 3. Presents the link between nitrogen intake and nitrogen loss among various animal categories, including lactating cows, dry cows, heifers, and calves. The coloured regression lines illustrate the variation of nitrogen excretion in relation to intake, with unique slopes reflecting the strength of the relationship for each category

reduced excretion per unit of intake. The y-intercept of 0.447, even though mathematically significant, possibly indicates baseline metabolic nitrogen losses occur even at low intake levels, yet are not biologically meaningful at zero intake.

In contrast, dry cows (red line, y=0.368+0.173x) shown a more pronounced correlation between intake and excretion, characterized by a slope of 0.173. This indicates that nitrogen excretion rises significantly more with intake than in lactating cows. Dry cows indicate reduced needs for nitrogen since they are not engaged in milk production, leading to a higher percentage of nitrogen being excreted instead of being used for productive roles.

Heifers (green line, y=0.141+0.249x) exhibited a moderate correlation between nitrogen intake and excretion, showing a slope of 0.249. Heifers are in a developmental stage, resulting in nitrogen for the growth of muscle and tissue. The slope indicates a relationship between nitrogen utilization for growth and its excretion, showing a moderate increase in nitrogen excretion as intake rises. Calves (yellow line, y=−0.00198+0.483x) demonstrated the most determined slope (0.483), implying that a considerable amount of nitrogen intake is released as waste. The finding is characteristic of child animals, as their digestive and metabolic systems are in the process of maturation, leading to a reduced efficiency in nitrogen utilization when compared to their older animals. The negative intercept, even though lacking biological significance, indicates the model's baseline and implies minimal excretion at extremely low intake levels.

The variations in slopes across all categories point out the distinct nitrogen requirements and utilization efficiencies. Lactating cows exhibit a highly efficient utilization of nitrogen, characterized by relatively low excretion rates per unit of intake, in comparison to calves, with the least efficiency in this regard. Dry cows and heifers shown moderate results, where nitrogen excretion shows an average increase in relation to intake.

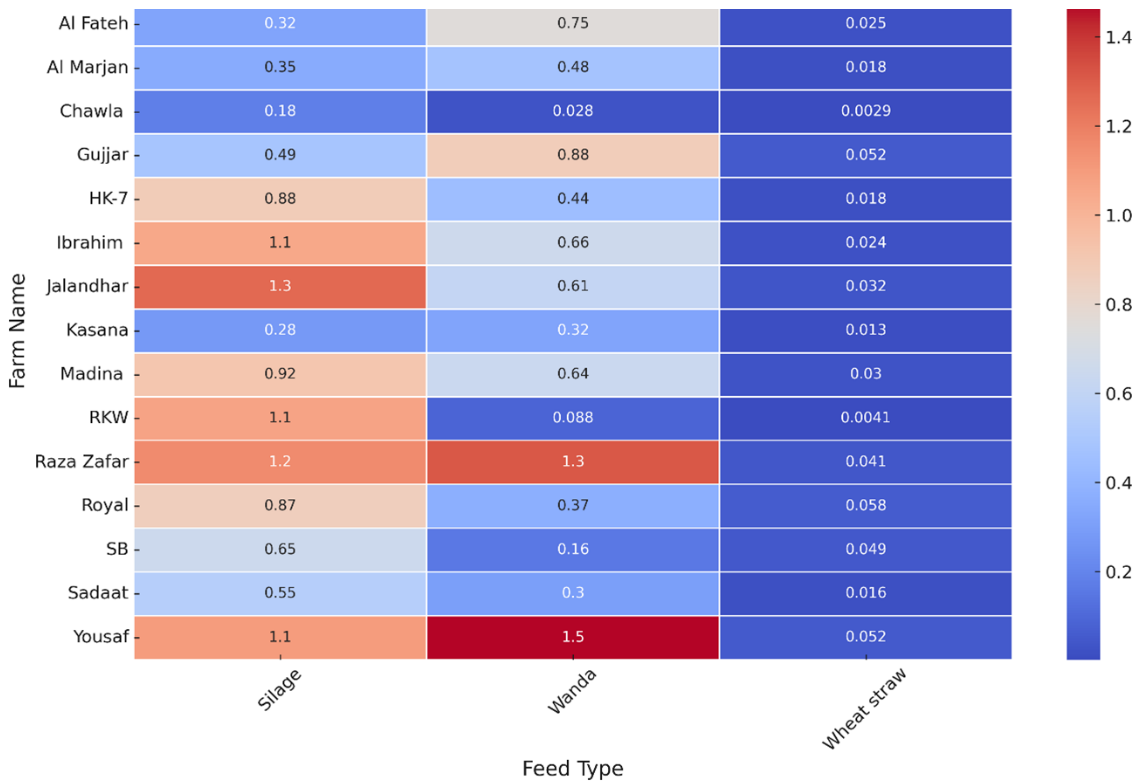

Figure 4. Shows the comparison of nitrogen intake and nitrogen efficiency across dairy farms, categorized by feed types (Silage, Wanda, Wheat Straw). Higher nitrogen intake and lower nitrogen efficiency (indicating more nitrogen loss) are represented by red shades, particularly for Wanda, while lower values (more efficient nitrogen use) are shown in blue, indicating better nitrogen retention or smaller herd sizes

Feed-specific nitrogen intake and manure output patterns in dairy farms

The heatmap in figure 4. provides a detailed comparison of nitrogen intake and manure output across 15 dairy farms, categorized by three primary feed types: Silage**,** Wanda, and Wheat Straw**.** The color gradient, ranging from blue to red, represents the amount of nitrogen intake and subsequent manure output, with red indicating higher values and blue indicating lower values. Farms like Raza Zafar**,** Yousaf**,** and Jalandhar show particularly high nitrogen intake and manure output for Wanda, highlighted in red, indicating a strong correlation between high nitrogen content in this feed and increased excretion. In contrast, farms like Chawla**,** Kasana, and RKW exhibit lower nitrogen intake and manure output across most feed types, especially in wheat straw, which is represented in blue, suggesting a more efficient use of feed nitrogen or smaller herd sizes. Wanda, a nitrogen-rich feed, generally results in the highest nitrogen intake and manure output compared to silage and wheat straw, as evidenced by the red and orange colors associated with many farms. This suggests that farms relying heavily on Wanda may need to implement more severe manure management practices to mitigate nitrogen losses. Meanwhile, wheat straw tends to have lower nitrogen content and contributes to reduced nitrogen intake and excretion. Overall, the heatmap highlights the significant variation in nitrogen efficiency across farms and feed types, with certain farms and feed combinations showing greater potential for nitrogen losses, warranting tailored nutrient management strategies to reduce environmental impact.

Bubble plot analysis of manure management system

In figure 5 the bubble chart depicts flush systems in the lowest nitrogen range**,** Slatted Floor and Drylot systems in the highest**,** and Bedded Pack farms displaying inconsistent

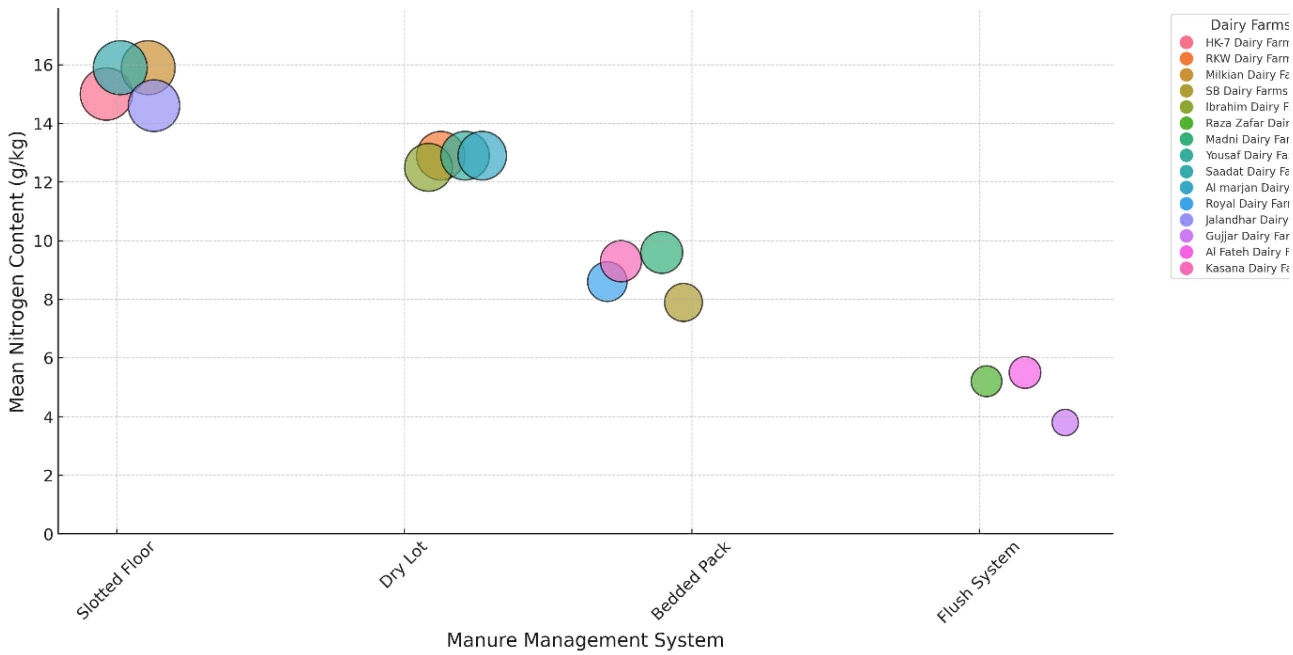

Figure 5. Bubble plot showing nitrogen retention across different manure management systems with ANOVA: F = 169.14, *p* < 0.001

nitrogen retention**,** highlighting the need for optimized management practices**.** The statistical analysis confirmed a significant effect of manure management systems on feces nitrogen content **(**ANOVA: F = 169.14, p < 0.001**).** Flush Systems retained the lowest nitrogen (3.8–5.5 g kg^{-1}, $p < 0.05$)**,** may be indicating higher nitrogen losses through volatilization or leaching. In contrast, Slatted Floor and Drylot systems retained the highest nitrogen levels (>12 g kg^{-1})**,** demonstrating greater nitrogen conservation. The Bedded Pack system showed high variability**,** with four farms (SB Dairy, Madni Dairy, Royal Dairy, and Kasana Dairy) recording nitrogen levels below 10 g kg^{-1}**,** suggesting inefficiencies due to bedding composition, aeration, or microbial activity**.**

Discussion

The analysis of herd size distribution revealed a bimodal pattern, with the majority of farms operating within the 175–225 animal range, while a secondary peak was observed in the 50–100 animal range. This suggests that medium-to-large farms dominate the industry, likely due to their ability to balance productivity and financial sustainability, while smaller farms remain relevant by serving localized markets. The limited number of large-scale farms (>300 animals) highlights the financial and operational challenges associated with managing extensive dairy operations. These findings emphasize the need for differentiated support strategies, where medium-to-large farms may benefit from efficiency optimization programs, while smaller farms require policies that enhance their market competitiveness and sustainability. Similar trends have been reported by Rojas-Downing (2017) and Georgieva (2024) and who highlighted that mid-sized dairy farms tend to maintain a balance between economic feasibility and operational efficiency.

The relationship between dry matter intake (DMI) and manure generation demonstrated a strong positive correlation (r = 0.87), confirming that feed consumption is a major determinant of manure output. Among the different cattle categories, lactating cows exhibited the highest DMI (23.5 kg d^{-1}), but their nitrogen excretion per unit of intake was relatively low ($y = 0.447 + 0.102x$). This trend suggests efficient nitrogen utilization for milk production. Similar findings were noted by Yang *et al.* (2022), who reported that increased DMI correlates with higher nitrogen efficiency due to milk protein synthesis. In contrast, dry cows ($y = 0.368 + 0.173x$) had higher nitrogen excretion, as they lack the productive demands of lactation, making them a key target for dietary optimization to reduce nitrogen losses. Johnson *et al.* (2016) also confirmed that non-lactating cows tend to excrete a higher proportion of dietary nitrogen, reinforcing the need for protein-adjusted diets. Heifers ($y = 0{\cdot}141 + 0{\cdot}249x$) retained moderate amounts of nitrogen, consistent with nutrient requirements for muscle and tissue accretion, but calves ($y = -0{\cdot}00198 + 0{\cdot}483x$) were the least efficient, reflecting their immature digestive tracts as a significant portion of the nitrogen was likely wasted. Our results indicate that nitrogen efficiency and environmental nitrogen loss improvement should be targeted to specific cattle categories with precision feeding strategies. Further reconciliation of data by regression analysis of all nitrogen intake and excretion; show that different classifications of similar cattle have clearly different efficiencies utilizing the nitrogen within their diet. The lowest nitrogen excretion per unit of intake was recorded for lactating cows, supporting previous studies showing milk protein synthesis as a mechanism of high nitrogen retention (Edouard *et al.*, 2016).

The highest excretion rate found in the calves, indicates a need for improved protein efficiency in the early stages of growth, which may be obtained through dietary strategies that increase microbial nitrogen capture in the rumen (Estermann *et al.*, 2002; Zanton and Heinrichs, 2008; Guo *et al.*, 2024). Yang *et al.* (2022) and van Gastelen *et al.* (2024) suggested that diet formulation needs to be adopted by the stage of cattle development. These findings emphasise the requirement for improved feeding regimens intended for the different designs of nitrogen retention in the various classifications of cattle. Farm-level nitrogen management is therefore highly dependent on the composition of feed that will help to determine nitrogen intake, utilization, and subsequent excretion patterns at the farm level, well beyond efficiencies at the animal level.

In a heatmap analysis, each of the feed types analyzed presented a distinct pattern corresponding to the efficiency of nitrogen under the type of feed used by the animals (Cantillon *et al.*, 2024), reinforcing that diets with high-type Wanda/concentrate are an excessive nitrogen source with a high contribution to nitrogen excretion, which shows that high protein concentrates are the main contributor to nitrogen balance problems in the environment (Vicente *et al.*, 2021). Conversely, diets based on silage and wheat straw were more favorable in terms of nitrogen utilization due to their more balanced protein:energy ratio, thus, promoting microbial nitrogen retention in the rumen (Leduc *et al*., 2023). Research by Ferrero *et al.* (2025) suggested that legume silages were effective in increasing nitrogen retention since this contributes to reductions of nitrogen losses from manure.

This suggests that feed formulation should be carefully managed to balance productivity and environmental sustainability, with protein-rich concentrate feeds being optimized to prevent excessive nitrogen excretion. Farms utilizing high-concentrate diets may need to lower crude protein intake and adopt manure management practices such as solid-liquid separation and manure acidification to mitigate nitrogen losses (Menezes *et al.*, 2016; Zhang *et al.*, 2024). The bubble plot analysis revealed important information on manure management efficiency, showing that Flush Systems retained the least amount of nitrogen (3.8–5.5 g kg^{-1}, $p < 0.05$) owing to the high risks of nitrogen volatilization and leaching. In evidence of this, Chauhan *et al.* (2025) ;Ross *et al.* (2021) and Li (2009) calculated that flush systems can decrease ammonia emissions by as much as 72% but can also increase nitrogen leaching when not managed appropriately. While Flush Systems have a higher potential to decrease ammonia emissions, they require more frequent removal of manure and require better nutrient recovery strategies to avoid nitrogen runoff (Vanotti *et al.*, 2020).

Conversely, Slatted Floor and Drylot systems had the best performance in retaining nitrogen (>12 $^{g\ kg}$), implying higher nitrogen conservation by limiting contact time for manure and consequently less nitrogen loss through volatilization. Retz et al. Slatted floors are most effective if combined with high frequency manure removal such that there is no risk for high rates of nitrogen volatilization (Vitaliano *et al.*, 2024). In contrast, the Bedded Pack systems were quite variable with some farms demonstrating low nitrogen retention (<10 g kg^{-1}), which was not expected. It indicates that bedding material, microbial activity, and aeration are important factors for the conservation of nitrogen because long-term storage of manure can favor microbial denitrification, which consequently increases nitrogen losses (Garlipp *et al.*, 2011; Eberl *et al.*, 2024). These results highlight the importance of adapting manure management systems to optimize nitrogen retention, particularly for Bedded Pack systems, where aeration and bedding turnover must be improved to enhance nitrogen conservation efficiency.

Collectively, these results illustrate the potential synergy between precision feeding and well-managed manure management systems to minimize nitrogen losses and balance the demands for an economically viable, yet environmentally sound dairy cattle production system. This underscores the key fact that only lactating cows are nitrogen efficient, and therefore, a sound feeding strategy for dry cows, heifers and calves should be aimed at reducing nitrogen excretion. Similar adjustments in dietary protein according to physiological needs reduce N losses in practice as shown in the present study results, particularly in line with recent findings on the possibility for significantly reducing the crude protein level for dry cows and heifers (Chowdhury *et al.*, 2024).

Conclusion

Optimized protein intake helps to reduce the Nitrogen content in dairy waste. Furthermore, the slatted floor collected waste retained more nitrogen content that can be further utilized as a nitrogen fertilizer source in the fields. By aligning feeding strategies, manure management, and environmental considerations, dairy farms can achieve greater nitrogen use efficiency while minimizing nitrogen losses to the environment. These findings provide a strong foundation for policy development and farm-specific recommendations aimed at improving sustainability in dairy production systems.

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