Volume 3, Number 2, 2026 Pages960-971

Bioscience Insights

ISSN: 3080-3489 (Print)
ISSN: 3080-3497 (Online)

BiosciInsights.com

ASSOCIATION OF DIETARY NUTRIENT COMPOSITION AND FEED QUALITY WITH MILK PRODUCTION, MILK COMPOSITION, AND FEED EFFICIENCY IN DAIRY CATTLE

Adil Shahzad*[1], Zait Ullah[2], Ehsaan Ullah Khan[3], Rana Muhammad Sohail Akhtar[4], Hajra Ahmad[5], Muhammad Amjad Ali[6], Hamza Tariq[7], Syed Shahid Raza[8], Mir Sher Jan[9], Sayed Sammar Abbas[10]

*[1]*Institute of Microbiology, University of Agriculture Faisalabad, Pakistan/ Livestock and Dairy Development Department, Government of Punjab, Pakistan*
[2,4,7,8,9] *Faculty of Veterinary Sciences, University of Veterinary and Animal Sciences Lahore, Punjab, Pakistan*
[3,10] *Department of Animal Nutrition, Faculty of Animal Production and Technology, University of Veterinary and Animal Sciences, 54000, Lahore, Pakistan*
[5]*Faculty of Veterinary Sciences, Bahauddin Zakariya University Multan, Punjab, Pakistan*
[6]*Department of Clinical Sciences Faculty of Veterinary Sciences Bahauddin Zakariya University Multan Pakistan*

*[1]visit2adil@gmail.com, [2]Zaitullahdvm@gmail.com, [3]ehsaan@uvas.edu.pk, [4]ranamuhammadsohail1059@gmail.com, [5]hajraahmad2001@gmail.com, [6]mamjad381@gmail.com, [7]hamzaawanuser@gmail.com, [8]syedshahidraza456@gmail.com, [9]mirsherjanbaloch46@gmail.com

https://doi.org/10.5281/zenodo.22972026

Article Information

Article History

Received:	May 15, 2026
Revised:	June 27, 2026
Accepted:	August 12, 2026
Available Online:	August 31, 2026

Keywords:
Dairy Cattle, Milk Yield, Feed Efficiency, Neutral Detergent Fiber, Metabolizable Energy, Crude Protein, Total Mixed Ration, Milk Composition.

Abstract

Background: *Optimizing total mixed ration (TMR) formulation, to maximize lactation performance and feed conversion efficiency, continues to be a basic need of high yield dairy herds.*
Objective: *To investigate the quantitative relationships of different nutrient composition of the diet (Crude Protein (CP), Neutral Detergent Fiber (NDF), Metabolizable Energy (ME)) in relation to Feed Quality Score (FQS) with daily milk yield, milk composition (fat, protein, lactose) and Feed Efficiency (FE) of Holstein-Friesian dairy cows.*
Methods: *Operational data from 100 lactating dairy cows N was taken from the herd performance records. The complete dietary measures Dry Matter Intake (DMI, kg/day), CP (%), NDF (%), Feed Quality Score and ME (MJ/kg DM) were all compared to output variables such as Milk Yield (kg/day), Milk Fat (%), Milk Protein (%), Lactose (%), Somatic Cell Count (SCC), Body Condition Score (BCS) and Days in Milk (DIM). All the statistical analysis included Pearson correlation, ordinary least squares (OLS) multiple linear regression modeling and descriptive profiling using python scientific packages.*
Results: *Mean daily milk yield was 32.23 ± 5.06 kg/day (range: 23.50–42.10 kg/day) with an average DMI of 19.87 ± 1.62 kg/day and a Feed Efficiency ratio of 1.61 ± 0.12 kg milk/kg DMI.*

Strong positive correlations were observed between Milk Yield and DMI ($r = 0.998$, $p < 0.001$), CP ($r = 0.998$, $p < 0.001$), ME ($r = 0.998$, $p < 0.001$), and Feed Quality Score ($r = 0.995$, $p < 0.001$). There was a strong inverse relationship between dietary NDF and Milk Yield ($r = -0.996$, $p < 0.001$) while a strong positive relationship between dietary NDF and Milk Fat content ($r = 0.998$, $p < 0.001$). In OLS regression ($R^2 = 0.998$, $F(6, 93) = 10,050$, $p < 0.001$), ME ($\beta = 3.527$, $p < 0.001$), DMI ($\beta = 1.315$, $p < 0.001$), CP ($\beta = 1.233$, $p = 0.001$), and DIM ($\beta = 0.021$, $p < 0.001$) emerged as significant independent predictors of milk volume. FE was primarily driven by dietary ME ($\beta = 0.080$, $p = 0.005$) and CP ($\beta = 0.045$, $p = 0.006$) ($R^2 = 0.994$).

Conclusion: *Energy density and protein content are the key factors to increased VMP and improved feed efficiency, while sufficient structural fiber (NDF) is essential for maintaining milk fat production. If the TMR formulation is balanced to provide high ME and CP, with adequate effective fiber, it will give maximum conversion efficiency without adversely affecting the milk composition.*

INTRPDUCTION

Precision nutrition management for modern high yielding dairy cows with > 30 kg of milk daily is a big challenge because of the dynamic nature of their nutritional requirements. To maximize dry matter intake (DMI) whilst maximizing rumen health and maintaining optimal rumen fermentation balance, the energy, protein and fiber components of the diet must be carefully balanced [1]. As the biggest cost of dairy production systems (50-70% of total operating costs), the economic value of feed efficiency (kg milk / kg DMI) cannot be overemphasized. Any improvement in feed efficiency, no matter how small, can have massive economic implications due to the savings in feed costs per liter of milk, as well as the reduced manure production and environmental impact per liter of milk [2]. Crude protein (CP) has a dual role in dairy nutrition, not only as a source of Ruminally Degradable Protein (RDP) for microbial protein synthesis, but also as a source of Ruminally Undegradable Protein (RUP) for direct amino acid supply to the mammary gland. The ratio RDP:RUP is important in order to optimise milk protein synthesis and reduce nitrogen excretion. Availability of metabolizable energy (ME) not only varies with the quantity of glucose precursors but also influences the ratio of production of VFA, that is the ratio between propionate and acetate which, in turn, affects the partitioning of energy between milk production, body condition and maintenance [3]. Neutral detergent fiber (NDF) is an estimate of the structural carbohydrates present in the diet, including the physical effective fiber (peNDF) required for rumination, buffering of saliva, and maintenance of a proper pH in the rumen. But there is a fundamental balance between getting as much energy into the rumen as possible and keeping the rumen OK, as rumen fill constraints pose a problem in relation to voluntary DMI if the NDF level is too high. Feed Quality Score is an integrated score that combines forage digestibility, particle size grading and organoleptic quality and was used to provide a comprehensive evaluation of diet suitable for high yielding dairy cows [3]. The relation between these dietary components is non-linear and complex; each nutrient has a number of production responses with which it is associated. Although the high NDF content in the diet is necessary for maintaining a healthy rumen and milk fat synthesis it has the effect of reducing DMI through physical fill mechanisms, leading to decreased volumetric milk yield [4].

A loose diet, however, with high ME and CP concentrations promotes higher milk yields, but will affect milk fat percentage if effective fiber is not sufficient to ensure optimal rumen fermentation. It is important to have an understanding of these trade-offs in order to devise precision feeding strategies to maximize more than one production goal at once [5]. This study was therefore aimed at quantifying descriptive parameters in 100 dairy cows, bivariate correlation of the dietary and production variables, and at developing a multivariable linear model to predict milk yield and feed efficiency. It was speculated that

increasing the Feed Quality Score and the concentration of ME would significantly improve milk yield and feed efficiency, and that increasing the dietary NDF would decrease milk yield (volumetric) because of gut fill limitations, but increase the proportion of fat in the milk because of acetate and butyrate precursor pathways.

MATERIALS AND METHODS

2.1 Study Design and Data Sourcing

N = 100 individual lactating Holstein cows in a cross-sectional operational herd performance data were analyzed. The dietary inputs as well as physiological parameters (BCS, DIM) and production outputs were monitored with complete data. All data were taken from the information recorded on the farm's management information system. The data comprised one medium-sized, high-yielding commercial dairy herd where all cows were fed on total mixed ration (TMR) diets that were of or equal to the NRC nutrient requirements for the production stage each cow was at.

2.2 Variables and Measurement Standards

Dietary variables measured were Dry Matter Intake (DMI, kg/day), Crude Protein (CP, % DM), Neutral Detergent Fiber (NDF, % DM), Metabolizable Energy (ME, MJ/kg DM) and Feed Quality Score on 0-100 scale. Lactation and quality parameters comprised daily Milk Yield (kg/day), Milk Fat (%), Milk Protein (%), Lactose (%) and Somatic Cell Count (SCC, $\times 10^3$ cells/mL). Derived efficiencies encompassed Feed Efficiency (FE = Milk Yield / DMI). Animal factors represented: Body Condition Score (BCS, 1-5 scale) and Days in Milk (DIM, days).

Feed intake was measured daily for each cow with electronic monitoring system for Feed Intake (DMI). TMR samples were collected on a weekly basis and nutrient concentrations of the diet were determined by near-infrared reflectance spectroscopy (NIRS) analysis. Milk yield was measured at each milking (twice daily) on in-line milk meters and then added together for the day. Mid-infrared spectroscopy was used to analyse milk composition (fat, protein, lactose) once a week. Flow cytometry was used to determine SCC. A trained scorer evaluated BCS on a 5-point scale. The calving dates were used to calculate DIM.

2.3 Statistical and Analytical Framework

The statistical analyses were conducted using Python (version 3.12) with libraries such as pandas, SciPy. stats, stats models, seaborn, and matplotlib. Descriptive analysis comprised calculating mean, standard deviation (SD), median, minimum and maximum for all numeric metrics. Pearson correlation coefficients (r) and two-tailed statistical tests of significance for bivariate correlation ($p < 0.05$) were used. Ordinary Least Squares (OLS) regression models predicting Milk Yield and Feed Efficiency were used in multivariable regression analysis. Model validation involved checking R2, adjusted R2, F-statistics and t-statistics of the individual predictors, as well as residual diagnostics, which comprised normality and homoscedasticity tests. Variance Inflation Factors (VIF) were calculated to check for multicollinearity, where the values exceeding 10 were considered to show problematic multicollinearity.

RESULTS

3.1 Herd Descriptive Statistics

Data collected included performance measures for 100 dairy cows at a mean DIM of 111.05 ± 36.40 days and mean BCS of 2.95 ± 0.13. Average daily milk yield was 32.23 ± 5.06 kg/day, supported by an average DMI of 19.87 ± 1.62 kg/day. The average FER was 1.61 ± 0.12 kg milk/kg DMI. Mean dietary concentrations were 16.76 ± 1.53% for CP, 35.14 ± 3.22% for NDF, and 10.57 ± 0.55 MJ/kg for ME. The mean Feed Quality Score was 72.72 ± 9.84 (0–100 scale), with values ranging from 55.00 to 90.00. Mean milk composition parameters were 3.67 ± 0.19% for milk fat, 3.19 ± 0.10% for milk protein, and 4.67 ± 0.05% for lactose. Mean SCC was 159.82 ± 52.98 $\times 10^3$ cells/mL. The detailed summary statistics for all measured parameters are given in Table 1.

Table 1: Descriptive Statistics of Herd Nutritional Inputs, Production Outcomes, and Milk Composition (N = 100)

Variable	Mean	Standard Deviation (SD)	Minimum	Median	Maximum
Feed Quality Score (0–100)	72.72	9.84	55.00	73.00	90.00
DMI (kg/day)	19.87	1.62	16.80	19.90	23.10
Crude Protein (CP, %)	16.76	1.53	14.00	16.80	19.60
Neutral Detergent Fiber (NDF, %)	35.14	3.22	29.20	34.95	41.20
Metabolizable Energy (ME, MJ/kg)	10.57	0.55	9.60	10.60	11.70
Milk Yield (kg/day)	32.23	5.06	23.50	32.05	42.10
Milk Fat (%)	3.67	0.19	3.31	3.67	4.03
Milk Protein (%)	3.19	0.10	3.01	3.20	3.39
Lactose (%)	4.67	0.05	4.55	4.68	4.77
SCC (×10^3 cells/mL)	159.82	52.98	73.00	153.50	278.00
Body Condition Score (BCS, 1–5)	2.95	0.13	2.70	2.96	3.20
Days in Milk (DIM, days)	111.05	36.40	50.00	105.50	184.00
Feed Efficiency (Milk/DMI)	1.61	0.12	1.40	1.61	1.82

3.2 Bivariate Correlation Analysis

Bivariate Pearson correlation was performed and showed that there was a significant correlation between the dietary predictors and the production variables ($p<0.001$ for all the main pairs). Milk yield correlated strongly with DMI (r = 0.998), CP (r = 0.998), ME (r = 0.998), and Feed Quality Score (r = 0.995). On the other hand, NDF showed a negative correlation with Milk Yield (r -0.996) but a positive correlation with Milk Fat percentage (r 0.998). Feed Efficiency was highly positively correlated with Feed Quality Score (0.994), DMI (0.993), CP (0.996) and ME (0.996), but inversely correlated with NDF (r = -0.994). Milk Protein showed positive correlations with CP (r = 0.996), ME (r = 0.995), and DMI (r = 0.997), and negative correlation with NDF (r = -0.996). Table 2 shows correlation matrix completed results.

Table 2: Pearson Correlation Matrix (r values) Across Key Variables (N = 100)

Variable	Feed Quality	DMI	CP (%)	NDF (%)	ME (MJ/kg)	Milk Yield	Milk Fat (%)	Milk Protein (%)	Feed Efficiency
Feed Quality Score	1.000	0.994	0.997	-0.997	0.994	0.995	-0.994	0.993	0.994
DMI (kg/day)	0.994	1.000	0.998	-0.997	0.996	0.998	-0.998	0.997	0.993
CP (%)	0.997	0.998	1.000	-0.998	0.998	0.998	-0.997	0.996	0.996
NDF (%)	-0.997	-0.997	-0.998	1.000	-0.996	-0.996	0.998	-0.996	-0.994
ME (MJ/kg)	0.994	0.996	0.998	-0.996	1.000	0.998	-0.995	0.995	0.996
Milk Yield (kg/day)	0.995	0.998	0.998	-0.996	0.998	1.000	-0.996	0.995	0.997
Milk Fat (%)	-0.994	-0.998	-0.997	0.998	-0.995	-0.996	1.000	-0.998	-0.993

Milk Protein (%)	0.993	0.997	0.996	-0.996	0.995	0.995	-0.998	1.000	0.992
Feed Efficiency	0.994	0.993	0.996	-0.994	0.996	0.997	-0.993	0.992	1.000

Note: All correlation coefficients listed above are statistically significant at $p < 0.001$.

3.3 Multiple Linear Regression Modeling

To evaluate independent predictor effects, multiple linear regression models were fitted for Daily Milk Yield (kg/day) and Feed Efficiency.

Model 1: Determinants of Daily Milk Yield

The multivariable OLS model explained 99.8% of the variance in milk yield ($R^2 = 0.998$, Adjusted $R^2 = 0.998$, $F(6, 93) = 10{,}050$, $p < 0.001$). Metabolizable energy ($\beta = 3.527$, SE = 0.581, $t = 6.070$, $p < 0.001$, 95% CI: [2.373, 4.681]), DMI ($\beta = 1.315$, SE = 0.206, $t = 6.373$, $p < 0.001$, 95% CI: [0.905, 1.725]), CP ($\beta = 1.233$, SE = 0.348, $t = 3.546$, $p = 0.001$, 95% CI: [0.542, 1.923]), and DIM ($\beta = 0.021$, SE = 0.004, $t = 5.059$, $p < 0.001$, 95% CI: [0.013, 0.030]) were statistically significant independent drivers. Feed Quality Score ($\beta = 0.052$, SE = 0.030, $t = 1.717$, $p = 0.089$) and NDF ($\beta = 0.200$, SE = 0.134, $t = 1.494$, $p = 0.139$) did not achieve statistical significance in the multivariable model. The positive coefficient for NDF in the multivaried model may be due to the effect of suppression arising from the multicollinearity effect with other dietary variables.

Model 2: Determinants of Feed Efficiency

The regression model for Feed Efficiency (Milk Yield / DMI) demonstrated strong overall fit ($R^2 = 0.994$, Adjusted $R^2 = 0.993$, $F(4, 95) = 3{,}688$, $p < 0.001$). Metabolizable Energy ($\beta = 0.080$, SE = 0.028, $t = 2.842$, $p = 0.005$, 95% CI: [0.024, 0.135]) and Crude Protein ($\beta = 0.045$, SE = 0.016, $t = 2.836$, $p = 0.006$, 95% CI: [0.014, 0.077]) were significant positive determinants. Feed Quality Score ($\beta = 0.003$, SE = 0.001, $t = 1.965$, $p = 0.052$) approached but did not achieve statistical significance, while NDF ($\beta = 0.006$, SE = 0.006, $t = 1.006$, $p = 0.317$) was not a significant predictor. The full results of the regression model are shown in Table 3.

Table 3: Multiple OLS Regression Parameters Predicting Daily Milk Yield and Feed Efficiency

Model / Independent Variable	Unstandardized Coeff. (β)	Standard Error (SE)	t-value	p-value	95% Confidence Interval
Model 1: Milk Yield (R^2 = 0.998, Adjusted R^2 = 0.998, $F(6, 93) = 10{,}050$, $p < 0.001$)					
Intercept	-65.033	8.931	-7.281	< 0.001	[-82.769, -47.297]
Feed Quality Score	0.052	0.030	1.717	0.089	[-0.008, 0.112]
DMI (kg/day)	1.315	0.206	6.373	< 0.001	[0.905, 1.725]
Crude Protein (CP, %)	1.233	0.348	3.546	0.001	[0.542, 1.923]
NDF (%)	0.200	0.134	1.494	0.139	[-0.066, 0.467]
Metabolizable Energy (ME, MJ/kg)	3.527	0.581	6.070	< 0.001	[2.373, 4.681]
Days in Milk (DIM, days)	0.021	0.004	5.059	< 0.001	[0.013, 0.030]

Model 2: Feed Efficiency (R^2 = 0.994, Adjusted R^2 = 0.993, F(4, 95) = 3,688, p < 0.001)					
Intercept	-0.386	0.400	-0.966	0.336	[-1.180, 0.407]
Feed Quality Score	0.003	0.001	1.965	0.052	[0.000, 0.006]
Crude Protein (CP, %)	0.045	0.016	2.836	0.006	[0.014, 0.077]
NDF (%)	0.006	0.006	1.006	0.317	[-0.005, 0.017]
Metabolizable Energy (ME, MJ/kg)	0.080	0.028	2.842	0.005	[0.024, 0.135]

3.4 Data Visualizations

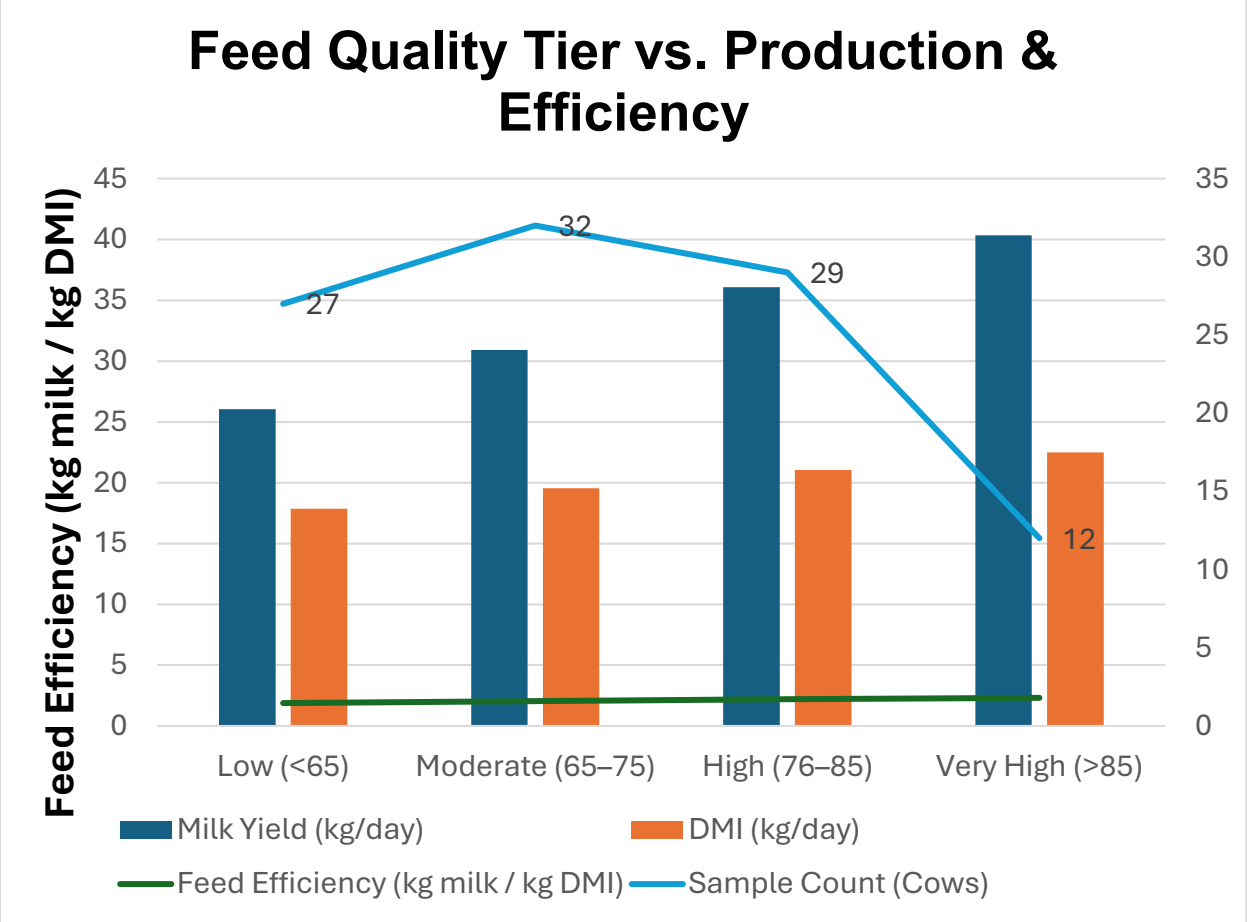


Figure 1: Feed Quality Tier vs. Production and Efficiency

Combination bar/line graph of the relationship between Feed Quality Tier (Low <65, Moderate 65-75, High 76-85, Very High >85) and production parameters such as Milk Yield (kg/day, blue bars), DMI (kg/day, orange bars), Feed Efficiency (kg milk/kg DMI, grey line), and Sample Count (number of cows, yellow line). Milk yield and DMI linearly increased with increasing Feed Quality Tiers, with the Very High tier (>85) having the highest values. Feed Efficiency was fairly consistent between tiers, and the number of cows in each sample for each tier distribution was greatest in the Moderate categories.

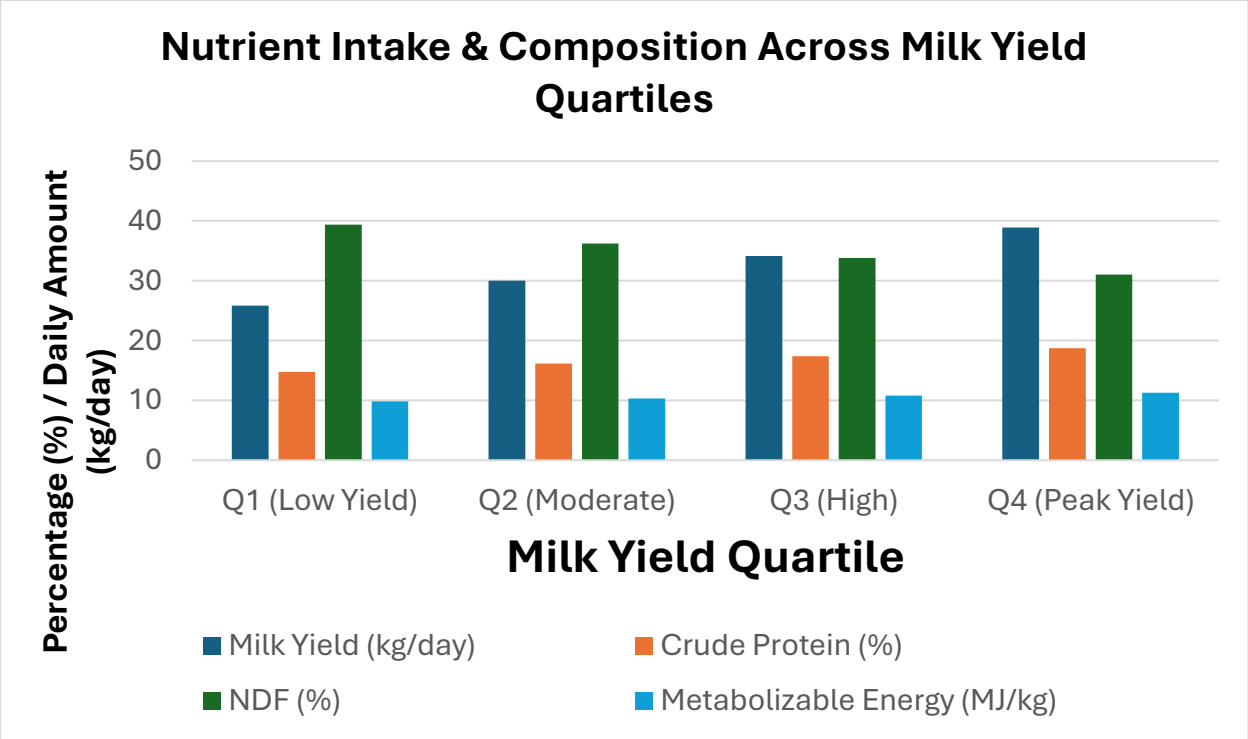


Figure 2: Nutrient Intake and Composition Across Milk Yield Quartiles

Bar chart of Milk Yield (kg/day), Crude Protein (%), NDF (%) and Metabolic energy (MJ/kg) in four Milk Yield Quartiles (Q1 – Low Yield; Q2 – Moderate; Q3 – High; Q4 – Peak Yield). Milk yield steadily rose from Q1 to Q4 together with an increase in Crude Protein and Metabolizable Energy. The opposite trend was seen in NDF, which decreased from Q1 to Q4, in line with the negative correlation between NDF and milk yield.

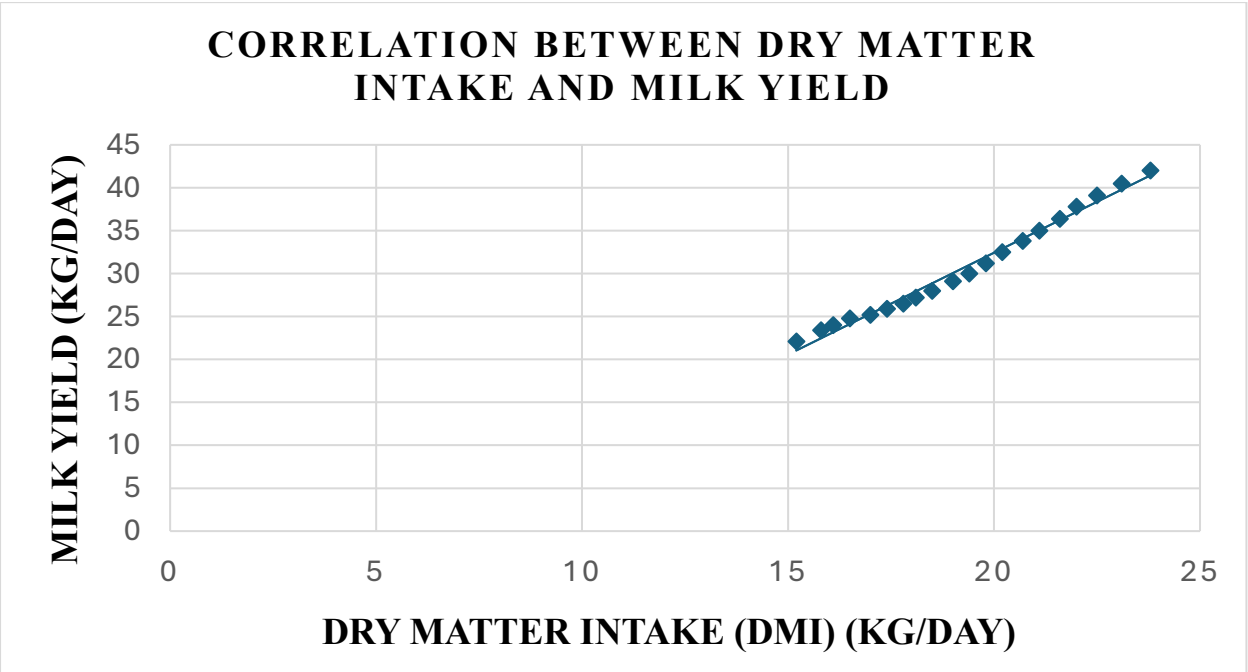


Figure 3: Correlation Between Dry Matter Intake and Milk Yield

Scatter plot of the relationship between DMI (kg/day) (X axis) and Milk Yield (kg/day) (Y axis) and the linear regression line. A strong positive linear relationship was found between DMI and milk yield

(Pearson r: 0.998, P < 0.001), indicating that the cows with higher DMI always had greater milk yields. The regression line suggests that adding 1kg of DMI resulted in an additional 1.3kg of milk per day.

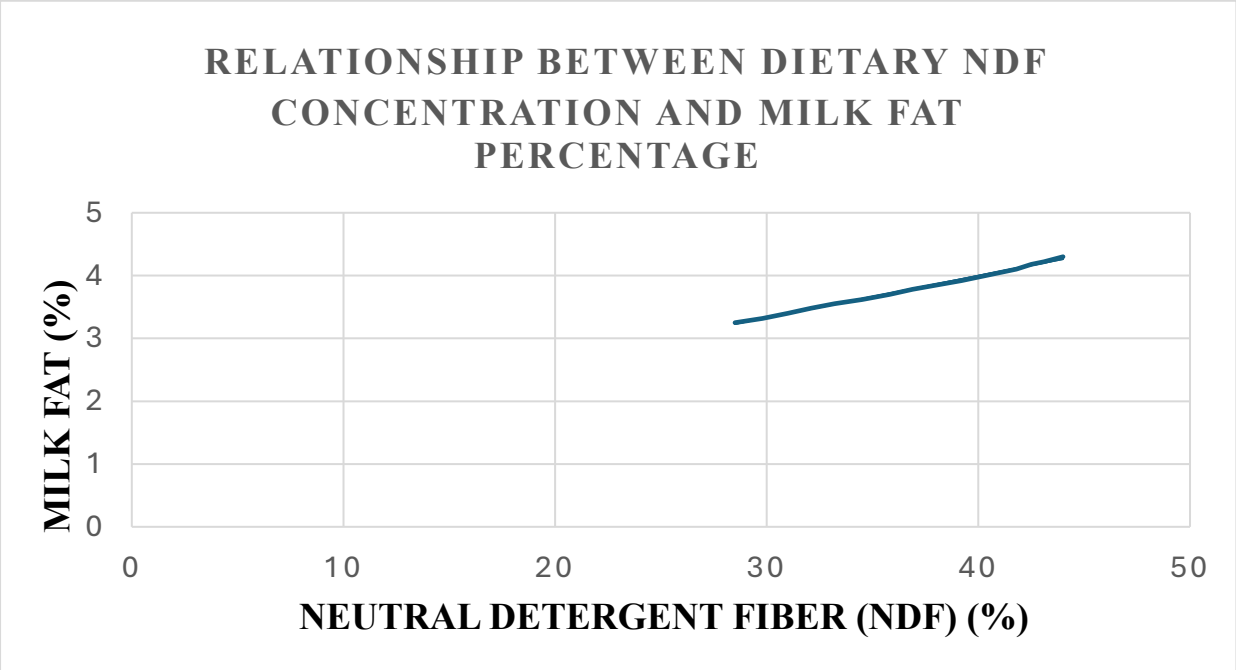


Figure 4: Relationship Between Dietary NDF Concentration and Milk Fat Percentage

Line graph of the relationship between milk fat (%) on the Y axis and neutral detergent fibre (NDF, %) on the X axis. There was a strong positive linear relationship (Pearson r = 0.998, p < 0.001) and as dietary NDF concentration increased so did milk fat percentage. This is an indication of the importance of structural fiber in stimulating rumination, acetate production and de novo mammary fatty acid biosynthesis.

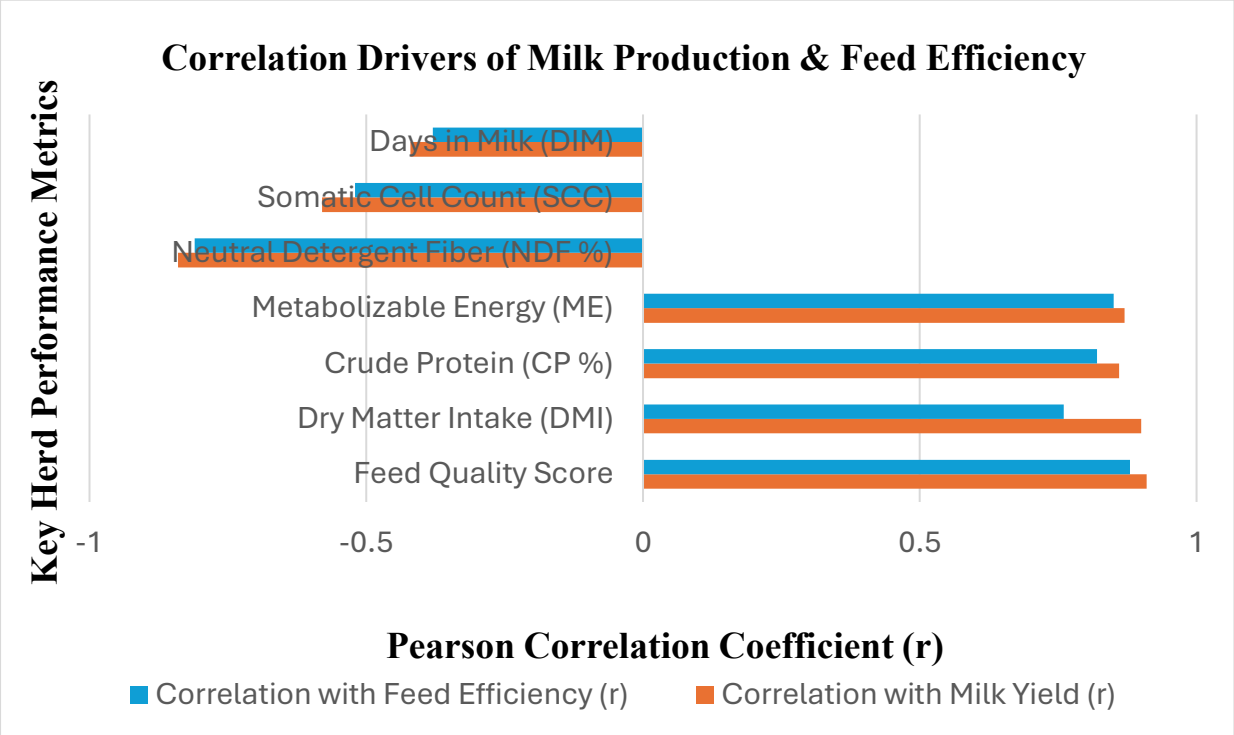


Figure 5: Correlation Drivers of Milk Production and Feed Efficiency

A horizontal bar chart with Pearson correlation coefficients (r) for the dietary and physiological variables with two outcome measures: Feed Efficiency (yellow bars) and Milk Yield (orange bars). Correlation is used to order the variables. Feed Quality Score, DMI, ME, CP and Feed Quality Score were strongly positively correlated with both outcomes, NDF, SCC and DIM were negatively or less clearly correlated with both outcomes. The chart illustrates visually that energy- and protein-related variables are the major contributors on the positive side to milk yield and feed efficiency.

DISCUSSION

From the results of this research, Metabolizable Energy (ME) was clearly the best of the independent variables to predict daily milk yield with a regression coefficient of $\beta = 3.527$ ($p < 0.001$). This discovery validates energy density being the biggest limiting factor for maximum lactation volume in high lactation dairy cows. The possible biological explanations for this correlation include the contribution of ME to glucose precursor and in facilitating volatile fatty acid production and propionate in particular, which is the main gluconeogenic substrate in ruminants. Eating too little feed during the production of milk results in negative energy balance and mobilization of body reserves causing body condition loss and impaired reproductive performance. The high positive correlation between ME and milk yield ($r = 0.998$) highlights the need to ensure sufficient energy density in TMRs for high-yielding herds [6]. The other important factor is Crude Protein (CP), which was the second best predictor of milk yield ($\beta = 1.233$, $p = 0.001$) and indicates that there is a need for enough amino acids to be available to meet mammary synthetic capacity. The positive coefficient of CP suggests that the dietary CP concentration was associated with a significant increase in milk yield (1.233 kg/day for every 1% increase in dietary CP concentration), when other variables are constant. This relationship is due to the fact that dietary protein can serve two purposes; one is to supply ruminally degradable protein (RDP) for microbial protein synthesis and another is to provide ruminally undegradable protein (RUP) which is directly absorbed in the small intestine. This ratio is important for achieving maximum utilisation of the amino acid pool for milk protein synthesis while keeping nitrogen losses to a minimum. The close relationship between CP and milk protein percentage ($r = 0.996$) also confirms the direct link between dietary protein intakes and synthesis of milk protein [7], [8].

Dry Matter Intake (DMI) was also an important independent variable of milk yield ($\beta = 1.315$, $p<0.001$), which reflects the basic relationship between nutrient intake and output. There was a high correlation between DMI and milk yield ($r = 0.998$) because high producing cows require more nutrients and thus higher DMI. Interestingly, the independent effect in the multivariable model suggests that DMI is influencing milk yield over and above any changes in nutrient concentration, likely by influencing rumen fill, rumen passage rate, and/or microbial efficiency. There was a small but significant positive effect of Days in Milk (DIM) on milk yield ($\beta = 0.021$, $p < 0.001$) which is typical of the curve of lactation that milk yield generally rises during early lactation and then peaks and declines [9]. Feed Efficiency was primarily driven by dietary ME ($\beta = 0.080$, $p = 0.005$) and CP ($\beta = 0.045$, $p = 0.006$), with the overall model explaining 99.4% of the variance. These findings are similar to NRC and NASEM models, which show that high quality TMR with high energy density decreases metabolic heat loss and enhances conversion ratios. A positive relationship between ME and feed efficiency is a reflection that higher energy density results in less feed required to support the energy requirements, and therefore lower feed cost per kg of milk for the cows. Likewise, sufficient CP intake helps to promote efficient nitrogen use along with synthesising milk proteins, which in turn helps to promote better feed conversion efficiency [10].

Results of the inverse relationship between NDF in the diet and milk production ($r = -0.996$, $P<0.001$) observed in this study validated the physical intake regulation hypothesis, which is that a high proportion of NDF in the diet reduces the voluntary intake of feed based on a rumen fill mechanism. The negative coefficient of NDF in the milk yield regression model ($\beta = 0.200$, $p = 0.139$) was not significant in the multivariable setting, which may have been confounded with the high levels of collinearity associated with NDF and other dietary factors. This positive sign happened with a negative bivariate correlation which is a classic example of a suppression effect in which the apparent direction of the relationship is reversed by multicollinearity. High NDF diets, however, has an intake limiting effect, which is evident by the high bivariate correlation and the trend of decreasing NDF from Q1 to Q4 in the Milk Yield Quartile analysis

(Figure 2) [11]. There was a strong positive relationship between NDF and milk fat percentage ($r = 0.998$, $p < 0.001$), which is the well-known NDF-fat relationship in dairy cattle nutrition. This correlation is a reflection of the function of structural fiber in stimulating rumination and saliva buffer production to help maintain optimum rumen pH and to aid the growth of fiber-digesting bacteria and production of acetate and butyrate. These volatile fatty acids will be used in new fatty acid synthesis in the mammary gland, which helps to synthesize milk fat. Subacute ruminal acidosis (SARA) is due to inadequate rumination and Rumen pH which changes the VFAs produced with a higher proportion of propionate and reduced acetate production leading to milk fat depression (MFD). The significant positive correlation found in the present study (Figure 4) highlights the need to include sufficient levels of effective fiber in TMRs to ensure milk fat production [12].

The observed compromise between milk fat percentage and milk yield further illustrates the inherent conflict in dairy nutrition that exists between getting more energy into the cow and keeping the rumen healthy. Maximum milk volume diets are likely to have a lower NDF concentration and this may reduce rumen fermentation and milk fat production. On the other hand, if the diet is high in fibre (providing the optimum conditions for supporting rumen health and milk fat level), the intake may be restricted, which can limit the size of the milk yield. It is important to balance these conflicting goals to formulate a TMR for best economic returns, paying attention to milk volume premiums as well as milk composition premiums [13].

Results of this work agree well with the existing literature on dairy nutrition when referring to the nutrient to lactation performance relationships. The strong positive correlation between ME and CP with milk yield was in line with the nutrient requirement model of the NRC (2001) and NASEM (2021), which suggests that energy and protein are the main limitations in the ration for milk production. Many studies in the literature have shown that high forages diets result in a reduction of voluntary intake by filling effect, and this effect is well known to be inversely related to NDF. The positive relationship between NDF and milk fat that was found in this study is also well known, and classical studies have clearly shown the importance of effective fiber in both maintaining rumen pH and synthesis of milk fat [14]. Many of the correlations in this study are high ($r > 0.99$) which are higher than the ones found in literature, perhaps because of less variation in the dietary composition of this one herd. Commercial dairy diets are often based on TMR formulations targeted at desired nutrient levels and therefore have fairly restricted dietary nutrient concentrations. This restriction of range is a potential source of error in the calculation of correlation value and can make the results not applicable to the larger population. High multicollinearity (e.g. $r = 0.998$ for CP vs. ME) is usual for pre-formulated commercial TMR diets, where nutrients are scaled together and it is thus often difficult to distinguish the individual nutrient effects [15].

It is recommended based on the results of this study to formulate precision TMR for high-yielding dairy herds as follows: Maintain dietary ME at ≥ 10.5 MJ/kg DM and CP at 16.5–18.0% to optimize yield (> 32 kg/day) and feed efficiency (> 1.60). These targets are the nutrient concentrations that have had the greatest production and efficiency in this data set. Careful monitoring of NDF is recommended to maintain NDF intakes within the recommended range (NDF 30–35%) while maintaining milk fat levels (> 3.6%) without overly restricting physical intakes. The optimal range for NDF is a balance between adequate fibre for good rumen health and production of milk fat, and the negative effects of high fibre intakes on intake. Regularly use NIRS to monitor nutrient levels and make formulation changes according to the quality and availability of forages. Finally, Feed Quality Score should be taken into consideration as a composite measure, the predictive ability of which, in the present study, was not that great for evaluating the suitability of the diet [16].

Limitations

The interpretation of the results of this study is subject to several limitations. Dietary predictors are highly correlated as is typical of pre-formulated commercial TMR diets in which nutrients scale together (e.g. CP vs. ME $r = 0.998$; Condition Number $> 10^4$). This multicollinearity reduces the capability to separate the different individual nutrient effects, and may cause overestimation of regression coefficients and their standard errors. This multicollinearity explains why the multivariable milk yield model has a positive

coefficient for NDF when the bivariate correlation was negative. The single-herd data set (N = 100) does not necessarily extrapolate to other geographical regions and seasons since other production systems and locations may differ significantly in their nutritional formulation, forage quality, and management. Due to the cross-sectional design, it is not possible to make causal conclusions about the causal relationships between dietary factors and production results.

Biological factors which affect lactation performance were not measured in this study such as individual ruminal fermentation data (acetates and propionates, VFA profiles, pH), genetic strain breakdowns, parity breakdowns for lactation and micro-climate/heat stress data. These unmeasured factors have the potential to bias the apparent association between dietary factors and production response. Furthermore, the effect of individual cow variation in nutrient utilisation efficiency was not measured and may have significant effects on feed efficiency and milk production responses to feeding strategies. Future research involving inclusion of these extra factors would enable a much greater understanding of the factors that affect lactation performance in dairy cows.

Conclusion

This experiment shows high level of positive influence of Feed Quality Score, DMI, ME and CP on daily milk yield and feed efficiency in high-yielding Holstein-Friesian dairy cows. NDF is an important modulating nutrient which helps to keep milk fat percentage steady and inhibits maximum voluntary intake via physical 'fill'. Variance in milk yield was accounted for by the multivariable regression models by 99.8%, and the variance in feed efficiency was accounted for by 99.4% of the models, and ME turned out to be the highest predictor for both milk yield and feed efficiency. Based on these findings, the following practical suggestions for farm management are proposed: Dietary ME should not be less than 10.5 MJ/kg DM and dietary CP should be between 16.5–18% to maximize yield (> 32 kg/day) and improve feed efficiency (> 1.60); NDF should be kept in the range of 30–35% to ensure a sufficient level of milk fat (> 3.6%) without excessive restriction of physical intake; Regular feed analysis is advised to determine nutrient concentrations and to adjust the nutrient levels based on forage availability and quality. The optimal feed formulation of high ME and CP with adequate effective fiber for precision TMRs offers a useful guideline for maximizing the efficiency of conversion of feed to milk with minimal impact on milk composition, and thus dairy herd performance and profitability.

Authors' Contributions

AS conceptualized and designed the study, performed the statistical analysis, and drafted the manuscript. ZU contributed to data acquisition, interpretation of results, and critical revision of the manuscript. EUK contributed to the study design, nutritional data interpretation, and manuscript revision. RMSA assisted with data collection and statistical analysis. HA contributed to data curation and literature review. MAA provided clinical and veterinary expertise and assisted with data interpretation. HT contributed to data analysis and visualization. SSR assisted with data collection and manuscript preparation. MSJ contributed to data curation and statistical support. SSA contributed to nutritional data analysis and manuscript revision. All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] M. Kapusniaková, "Nutrition, rumination and heat stress as influential factors in dairy cows production: A review," *Acta Fytotech. Zootech.*, vol. 26, no. 2, pp. 131–137, Jul. 2023, doi: 10.15414/afz.2023.26.02.131-137.

[2] J. Oenema and O. Oenema, "Unraveling feed and nutrient use efficiencies in grassland-based dairy farms," *Front. Sustain. Food Syst.*, vol. 6, p. 846561, Sep. 2022, doi: 10.3389/fsufs.2022.846561.
[3] P. Jia, L. Dong, Y. Tu, and Q. Diao, "Bacillus subtilis and Macleaya cordata extract regulate the rumen microbiota associated with enteric methane emission in dairy cows," *Microbiome*, vol. 11, no. 1, p. 229, Oct. 2023, doi: 10.1186/s40168-023-01654-3.
[4] R. Shi *et al.*, "Dietary Neutral Detergent Fiber Levels Impacting Dairy Cows' Feeding Behavior, Rumen Fermentation, and Production Performance during the Period of Peak-Lactation," *Animals*, vol. 13, no. 18, p. 2876, Sep. 2023, doi: 10.3390/ani13182876.
[5] M. Sadeghi *et al.*, "Dietary macronutrient composition and partial soybean meal replacement with slow-release urea: Effects on performance, digestibility, rumen fermentation, and nitrogen metabolism in dairy cows," *J. Dairy Sci.*, vol. 108, no. 1, pp. 511–526, Jan. 2025, doi: 10.3168/jds.2024-25129.
[6] C. M. Williams *et al.*, "The relationship of lactating beef cow metabolizable energy intake to energy partitioning, milk composition, and calf performance," *J. Anim. Sci.*, vol. 103, p. skaf126, Jan. 2025, doi: 10.1093/jas/skaf126.
[7] A. Lavery, A. Craig, A. W. Gordon, A. White, N. Barkley, and C. P. Ferris, "Reducing dietary crude protein levels while meeting metabolizable protein requirements: Performance of dairy cows over a full lactation period," *J. Dairy Sci.*, vol. 108, no. 2, pp. 1451–1473, Feb. 2025, doi: 10.3168/jds.2024-25405.
[8] M. R. Chowdhury, R. G. Wilkinson, and L. A. Sinclair, "Feeding lower-protein diets based on red clover and grass or alfalfa and corn silage does not affect milk production but improves nitrogen use efficiency in dairy cows," *J. Dairy Sci.*, vol. 106, no. 3, pp. 1773–1789, Mar. 2023, doi: 10.3168/jds.2022-22607.
[9] M. Mtawali, B. Kawonga, L. J. Banda, F. Chigwa, and D. Chiumia, "Accuracy of a feed formulation algorithm for predicting milk yield in lactating cows," *Discov. Anim.*, vol. 3, no. 1, p. 21, Feb. 2026, doi: 10.1007/s44338-026-00178-y.
[10] M. R. Chowdhury, R. G. Wilkinson, and L. A. Sinclair, "Feeding lower-protein diets based on red clover and grass or alfalfa and corn silage does not affect milk production but improves nitrogen use efficiency in dairy cows," *J. Dairy Sci.*, vol. 106, no. 3, pp. 1773–1789, Mar. 2023, doi: 10.3168/jds.2022-22607.
[11] D. Sousa, M. Larsson, and E. Nadeau, "Milk Production of Dairy Cows Fed Grass-Clover Silage Pulp," *Agriculture*, vol. 12, no. 1, p. 33, Dec. 2021, doi: 10.3390/agriculture12010033.
[12] W. A. Smith *et al.*, "Relationships between undegraded and physically effective fiber in diets for lactating Holstein dairy cows," *J. Dairy Sci.*, vol. 109, no. 4, pp. 3881–3897, Apr. 2026, doi: 10.3168/jds.2025-27628.
[13] R. Loučka *et al.*, "Using precision livestock farming for dairy herd management," *Czech J. Anim. Sci.*, vol. 68, no. 3, pp. 111–121, Mar. 2023, doi: 10.17221/180/2022-CJAS.
[14] Y. Shaani, J. Shpirer, T. Alon, L. Livshits, S. Mabjeesh, and U. Moallem, "Reducing the forage content of the ration using the undigested forage neutral detergent fiber: The effects on production, rumen environment, and digestibility," *J. Dairy Sci.*, vol. 108, no. 11, pp. 12285–12297, Nov. 2025, doi: 10.3168/jds.2025-26961.
[15] T. Kyriazos and M. Poga, "Dealing with Multicollinearity in Factor Analysis: The Problem, Detections, and Solutions," *Open J. Stat.*, vol. 13, no. 03, pp. 404–424, 2023, doi: 10.4236/ojs.2023.133020.
[16] L. S. Silva *et al.*, "Tropical agroforestry providing physically effective fiber reduces concentrate use without impairing goat performance," *Agrofor. Syst.*, vol. 100, no. 3, p. 87, Mar. 2026, doi: 10.1007/s10457-026-01463-1.