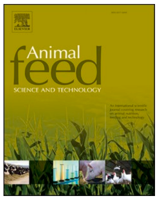
Animal Feed Science and Technology 331 (2026) 116595

Contents lists available at ScienceDirect

Animal Feed Science and Technology

journal homepage: www.elsevier.com/locate/anifeedsci



Evaluation of concentrate feeding strategies in an intensive grass silage-based dairy production system

Sari Kajava [*], Auvo Sairanen, Marketta Rinne

Natural Resources Institute Finland (Luke), Finland

ARTICLE INFO

Keywords:
Dairy cow
energy balance
feed efficiency
forage proportion
early lactation
late lactation

ABSTRACT

Environmental and societal pressures are encouraging to reduce the proportion of concentrate feeds in grass-based dairy production systems. The objective of this experiment was to compare two concentrate feeding strategies to reduce the concentrate use in dairy cow diets: 1) a constant concentrate proportion of 35 % throughout the lactation period, and 2) an adjusted strategy with 45 % in early lactation (EL) and 25 % in late lactation (LL). The strategies were simulated in two separate and parallel 8-week sub-experiments for EL and LL, each including a common concentrate level of 35 %. In EL, the comparison was made against 45 %, and in LL against 25 %. The strategies were indirectly compared based on production responses. Sub-experiments were conducted with 20 multiparous Nordic Red cows per lactation stage. Higher concentrate in EL (EL-45) increased energy-corrected milk, fat and protein yields compared to EL-35, with no significant differences in body weight change, energy balance or plasma BHBA and NEFA concentrations. The production response to concentrate supplementation was greater in EL than LL (1.3 and 0.9 kg ECM per kg additional concentrate, respectively). In LL, feed efficiency was higher, and body weight gain was lower with the lower concentrate diet. These findings suggest that under current feed prices, prioritising concentrate use in early lactation and reducing it in late lactation is more cost-effective and helps limit excessive body weight gain in late lactation.

1. Introduction

Ruminants, unlike monogastric animals, can synthesise all required energy and protein by consuming only grass forages (Randby et al., 2012; Steinshamn and Thuen, 2008). Despite this, concentrate feeds are widely used in dairy production due to the positive milk production responses they elicit (Sairanen et al., 2022), especially when milk price is high relative to concentrate costs. However, increasing environmental and societal pressures may encourage a transition towards more grass-based feeding systems, as grasslands offer significant advantages over arable cropping in terms of greenhouse gas mitigation and ecosystem services (Bengtsson et al., 2019; Saarinen et al., 2019; Sairanen et al., 2024).

Abbreviations: BHBA, beta-hydroxybutyrate; BW, body weight; BWC, body weight change; BCS, body condition score; CP, crude protein; DM, dry matter; DOM, digestible organic matter; ECM, energy-corrected milk; EL, early lactation; K_l, efficiency of utilisation of ME for milk production; LL, late lactation; ME, metabolizable energy; MP, metabolizable protein; NDF, neutral detergent fibre; NEFA, non-esterified fatty acids; NUE, nitrogen use efficiency in milk production; OMD, organic matter digestibility; OMS, in vitro organic matter pepsin-cellulase solubility; SDMI index, relative intake potential of silage dry matter; SR, substitution rate; TMR, total mixed ration; VFA, volatile fatty acids; WSC, water soluble carbohydrates.

* Correspondence to: Natural Resources Institute Finland (Luke), Halolantie 31 A, Maaninka 71750, Finland.
E-mail address: sari.kajava@luke.fi (S. Kajava).

https://doi.org/10.1016/j.anifeedsci.2025.116595
Received 5 September 2025; Received in revised form 31 October 2025; Accepted 1 December 2025
Available online 4 December 2025

Assessing the impact of reduced concentrate use in dairy cow diets requires evaluation across the entire lactation period. Concentrate feeding strategies can be carried out as constant or variable forage to concentrate ratio during the lactation. According to Mäntysaari et al. (2003), (2004) the variable concentrate feeding strategy (higher in early lactation and gradually decreasing towards late lactation) had no advantage for milk yield of primiparous cows compared to a constant level, when the total amount of concentrates consumed over the whole lactation was the same. This contradicts the hypothesis where concentrate supplementation response depends on energy balance of cows (Sairanen and Huhtanen, 2024) or lactation stage (Kirkland and Gordon, 2001). Concentrate supplementation response is high when cow's energy balance is negative during first weeks of lactation or when the diet energy level is low. Still, the production response to increased concentrate feeding was shown not to be dependent on the production level of the cow (Huhtanen and Nousiainen, 2012).

In early lactation, the onset of milk production results in a significant increase in energy consumption of the cow as the peak of feed intake is achieved later than that of milk production (Rukkwamsuk et al., 1999). This causes a negative energy balance (Berry et al., 2006) and excessive body tissue mobilisation (Rico and Barrientos-Blanco, 2024) increasing the risk of metabolic diseases (Rukkwamsuk et al., 1999). A conventional approach to alleviate negative energy balance in dairy cows is to increase the concentrate level in the diet. However, this often leads to a corresponding increase in milk yield (Kokkonen et al., 2000), and thus may not necessarily improve the cow's energy balance. However, there is some earlier evidence that variable forage to concentrate ratio (higher concentrate feeding in early and lower in late lactation) can be beneficial in terms of energy balance and fertility (Everson et al., 1976; Keys et al., 1983).

During late lactation, the energy status of the cows is typically positive as the energy supply from the diet is often greater than the energy consumed for milk production. This results in body weight (BW) and body condition score (BCS) gain of the animals (Miller et al., 1969; Roche et al., 2009). A declining concentrate feeding strategy and thereby lower energy intake can reduce the weight gain of cows during the late lactation, which can further have positive effects at the beginning of the next lactation period (Kokkonen et al., 2005; Rathbun et al., 2017).

The main objective of the present study was to compare two concentrate allocation strategies for dairy cows in intensive grass silage-based milk production systems, with the aim of reducing the proportion of concentrates in the diet. Two sub-experiments were conducted simultaneously using early- and late-lactating dairy cows. The feeding strategies evaluated were:

1. Constant concentrate level during early and late lactation
2. Higher concentrate proportion in the early lactation diet and lower concentrate proportion in the late lactation diet

We hypothesised that the response of milk yield to concentrate feeding would be greater during early lactation due to differences in feed efficiency and energy balance between lactation periods. Secondly, we hypothesised that higher concentrate feeding does not alleviate the negative energy balance of cows during early lactation, whereas a lower concentrate level would decrease the positive energy balance in cows during the late lactation period.

2. Materials and methods

2.1. Animals, diets and experimental design

The experiments were conducted at Natural Resources Institute Finland (Luke), Jokioinen (60°48′N, 23°29'E), Finland, during spring 2023. The experiments were approved by the National Ethics Committee (Hämeenlinna, Finland, license number ESAVI/45876/2022).

The experiment consisted of two dairy cow sub-experiments conducted during early lactation (EL) and late lactation (LL). The experiments were conducted simultaneously each using 20 multiparous Nordic Red dairy cows, that were automatically identified at milking parlour, weight scales, feeding area and concentrate feeders by transponder collars. The cows were kept in a loose-house dairy barn and milked twice a day in a 2 × 6 auto tandem milking parlour at 0700 and 1700 h. After each milking, cows were weighed by a walk-through static scale (Pellon Group Ltd., Ylihärmä, Finland). Each cow had a specified individual total mixed ration (TMR) feeding place equipped with physical separators between the places, that registered their daily feed intake (Insentec BV, Marknesse, the Netherlands). Cows were fed TMR for *ad libitum* intake, and it was delivered to cows daily at 0700, 1300, 1600, and 1830 h by an automatic feeding wagon (TR Feeding Robot, Pellon Group Ltd., Ylihärmä, Finland), which also weighed the amount of TMR given to the cows. A target of 5 % of feed refusals was used to ensure *ad libitum* feed intake of cows. Uneaten feed was removed and weighed daily at 1200 h before offering fresh feed. Cows also received pelleted concentrate mix provided by automatic concentrate feeders (Pellon Ltd., Ylihärmä, Finland) and during milkings at the milking parlour, and had free access to drinking water.

The silage used in the experiment was made of a primary growth mixed timothy (*Phleum pratense*) and meadow fescue (*Festuca pratensis*) sward during the growing season 2022. The grass was wilted, precision chopped and ensiled in a bunker silo and treated with 5 l per ton of a formic and propionic acid-based additive (AIV® 2 Plus Na, Eastman, Oulu, Finland).

The experimental diets (Table 2) were fed as partial mixed rations. Diets were formed so that all cows received the same TMR with 25 % of concentrate (on dry matter (DM) basis) and experimental diets were adjusted to target concentrate levels using automatic concentrate feeders. The pelleted concentrate mixture in the TMR consisted of oats, rapeseed meal and a mineral supplement, with the following ratios on DM basis: 445:501:54. The pelleted concentrate mixture delivered from concentrate feeders consisted of oats, barley, rapeseed meal, molassed sugar beet pulp and a mineral supplement with DM based ratios of 388:357:30:216:10, respectively. In addition, the cows received 0.6 kg barley-based pelleted concentrate at the milking parlour. The pelleted concentrate consisted of barley, wheat, molassed sugar beet pulp, rapeseed meal and a mineral supplement on air-dry based proportions of 362:170:140:298:30, respectively. In EL, the cows also received 200 ml/d of an energy supplement (Mestarin Proppi, Lantmännen Agro Oy, Vantaa, Finland; 16.1 MJ/kg DM).

The targeted dietary concentrate proportions were 35 % and 45 % in early lactation (EL), and 25 % and 35 % in late lactation (LL), respectively. Due to practical constraints and adjustments made during the experimental setup, the LL diet originally intended to contain 25 % concentrate was ultimately formulated with a 27 % concentrate level. The chemical composition of the experimental diets is summarized in Table 1.

In EL, the cows started the experiment immediately after calving, when they weighed on average 690 ± 76.1 (mean ± standard deviation) kg. An average BCS was 3.6 ± 0.36 in the beginning of the experiment and the average parity was 3.3 ± 1.13. Primiparous cows were not included in the experiment. Cows were assigned to pairs based on their calving date, lactation number, BCS and milk yield of the previous lactation. Data collection of each animal lasted for 60 d.

The LL cows started the experiment simultaneously averaging 213 ± 27.1 days in milk and producing 31.6 ± 3.27 kg milk per day. The average weight of the cows was 671 ± 47.0 kg and BCS 3.3 ± 0.31. The average parity of the cows was 3.4 ± 1.32 and no primiparous cows were included in the experiment. Cows were assigned to pairs based on their BW change (BWC) before the experiment, milk yield, BCS and lactation number. Data collection lasted for 60 d.

2.2. Data and sample collection, and chemical analyses

The milk yield was recorded at every milking and feed intake measured daily during the entire experiments. In EL, milk samples (30 ml/sample) were collected from four consecutive milkings during lactation weeks 2, 3, 6 and 8. In LL, milk samples were collected from four consecutive milkings on the first experimental week, 30 d after the experiment started and during the last experimental week. Milk samples were analysed for fat, protein, lactose and urea in a commercial laboratory (Valio Ltd., Seinäjoki, Finland) using an infrared analyser (Milcoscan FT6000, Foss Electric A/S, Hillerød, Denmark). The morning and afternoon milk yields were used to calculate the weighted means of the milk composition.

In EL, blood samples for plasma non-esterified fatty acids (NEFA) and beta-hydroxybutyrate (BHBA) analyses were taken in weeks 1, 3 and 6 of lactation. Samples were taken from the coccygeal vein after the morning milking. Blood was collected in 10-ml EDTA tubes and centrifuged for 15 min at 2000 × g. Plasma samples were frozen and stored at −20°C. NEFA and BHBA concentrations were analysed by photometric enzymatic determination (Movet, Kuopio, Finland).

In EL, the BCS of the cows (a scale of 1–5: 1 = skinny to 5 = very fat) was determined three weeks prior to expected calving, and at the beginning and at the end of the experiment. LL cows were scored at the start and at the end of the experiment.

The DM content of the silage and TMR was measured twice a week, and that of concentrates once per month. The DM content of the samples was determined by drying the samples at + 105°C for 20 h and organic matter concentration by ashing at 600 °C for 2 h (method AOAC-942.05, Official Methods of Analysis of AOAC International 2019). Silage DM concentration was corrected for the loss of volatiles according to Huida et al. (1986).

Silage was sampled three times per week (300 g/sample), pooled as three-week samples for feed analyses and stored at −20 °C. Concentrate feeds were sampled once per week (500 g/sample) and pooled as four-week samples for feed analyses. Feed samples for chemical analysis were dried at + 50°C until dry. Feed samples were analysed at Luke laboratory using routine methods which follow the standard SFS-EN ISO/IEC 17025:2017 and is accredited by the Finnish Accreditation Service (Helsinki, Finland) with a number

Table 1
Chemical composition of the experimental feeds.

	Grass silage	Oats grains	Barley grains	Rapeseed meal	Molassed sugar beet pulp
Dry matter (DM), g/kg	256	902	888	868	876
In DM, g/kg					
Ash	76	33	25	87	45
Crude protein	159	112	120	358	102
Crude fat	na[b]	65	30	49	15
Crude fibre	-	106	38	133	194
Water soluble carbohydrates	53	na	na	na	na
Starch	na	491	660	25	29
Neutral detergent fibre	557	318	193	266	365
Feed values					
Metabolizable energy, MJ/kg DM	11.15	12.51	13.47	11.29	12.36
Metabolizable protein, g/kg DM	84.7	91	98	162	101
Protein balance in the rumen, g/kg DM	33	-23	-26	142	-47
Silage DM intake index	102				
Silage fermentation quality[a]					
pH	3.94				
Ammonia N, g/kg N	44				
Total volatile fatty acids	17.5				

[a] g/kg DM: Ethanol 7.9, lactic acid 54, formic acid 17.5, acetic acid 16.9, propionic acid 0.23, butyric acid 0.26
[b] Not analysed

Table 2
Ingredients of the experimental diets and their nutritional composition.

	EL-35[a]	EL-45[b]	LL-27[c]	LL-35[d]
Diet ingredients, g/kg dry matter (DM)				
Grass silage	650	550	730	650
Pelleted concentrate	350	450	270	350
Cereal grains[e]	543	613	454	540
Rapeseed meal	343	233	481	347
Molassed sugar beet pulp	75	125	13	74
Mineral supplement[f]	39	29	52	39
Chemical composition, g/kg DM (unless otherwise stated)				
Dry matter, g/kg	475	538	424	475
Ash	80	74	83	80
Crude protein	171	164	176	171
Neutral detergent fibre	453	424	476	453
Metabolizable energy, MJ/kg DM	11.4	11.6	11.2	11.4
Metabolizable protein	95	95	95	95
Protein balance in the rumen	33	24	39	33

[a] EL-35 = Early lactation diet with 35 % of concentrate in the diet
[b] EL-45 = Early lactation diet with 45 % of concentrate in the diet
[c] LL-27 = Late lactation diet with 27 % of concentrate in the diet
[d] LL-35 = Late lactation diet with 35 % of concentrate in the diet
[e] Grain = Oats 64–89 %, barley 8–35 %, and wheat 1–4 %.
[f] Mineral supplement = Commercial mineral mixture (Lypsykivennäinen Tiineys+, Hankkija Ltd., Hyvinkää, Finland; composition Ca 200 g/kg, P 14 g/kg, Mg 85 g/kg, Na 90 g/kg, Na-selenite (3bE8) 20 mg/kg, Se-methionine (3b8.11) 12 g/kg, Vitamin A 350 000 IU/kg, Vitamin D3 120 000 IU/kg, Vitamin E (3a700) 3000 mg/kg, D-biotine (3a880) 30 mg/kg), I 180 mg/kg, Co 25 mg/kg, Cu 650 mg/kg, Mn 3 180 mg/kg and Zn 5 350 mg/kg.

T024. Samples were analysed for nitrogen with the Dumas method using a Leco628 CHN-elemental analyser (Leco Corporation, St Joseph, MI, USA) and crude protein (CP) was calculated as N × 6.25. The neutral detergent fibre (NDF) concentration was analysed according to Van Soest et al. (1991), where sodium sulphite was used in NDF-detergent solution and a heat-stable alpha amylase used in samples containing starch and the results are presented ash-free (aNDFom). The silage samples were analysed for pH, concentrations of volatile fatty acids (VFA, Huhtanen et al., 1998), lactic acid (Haacker et al., 1983), water soluble carbohydrates (WSC; Somogyi, 1945), ammonia-N (McCullough, 1967) and in vitro organic matter pepsin-cellulase solubility (OMS) according to Nousiainen et al. (2003). The OMS (g/g OM) was converted to organic matter digestibility (OMD) using the primary growth equation for grass silages (0.077 + 0.86 × OMS) based on a data set comprising of Finnish in vivo digestibility experiments (Huhtanen et al., 2006).

2.3. Calculations and statistical analysis

The DM intake of the cows was based on the DM concentration of the TMR, while the feed value and nutrient intakes were calculated based on silage and concentrate samples analysed separately. The metabolizable energy (ME) concentration of silage was calculated in accordance with the Finnish feed evaluation system (Luke, 2025) on the basis of the digestible organic matter (DOM) content. For concentrates, the ME concentrations were calculated based on the chemical composition and digestibility coefficients of nutrients presented by Luke (2025). The ME intake of the cows was calculated by multiplying the feed intake by the respective feed ME concentrations, and subsequently corrected by taking into consideration the effects of diet composition and dry matter intake (Luke, 2025). The metabolizable protein (MP, indicated as amino acids absorbed from the small intestine) and protein balance in the rumen were calculated as presented by Luke (2025) for all feeds. The relative intake potential of silage dry matter (SDMI index) was calculated according to (Huhtanen et al., 2007). The energy-corrected milk (ECM) yield was calculated using the equation outlined by (Sjaunja et al., 1990).

The corrected ME intake of the cows was calculated as follows:

$$ME\ intake,\ \frac{MJ}{day} = ME\ intake\left(\frac{MJ}{day}\right) - \left[(-56.7 + 6.99 \times (ME\ content\ in\ the\ diet) + feed\ intake - 0.44595 \times (CP\ in\ the\ diet) + 0.00112 \times (CP\ in\ the\ diet)^2)\right]$$

The energy balance was calculated by subtracting the energy required for milk production and maintenance and BWC from the intake of ME. The energy value used for ECM production (5.15 MJ/kg ECM), ME requirements for maintenance (0.515 MJ × kg $BW^{0.75}$) and BWC (34 MJ × kg BW increase or 28 MJ × kg BW reduction, MJ/day) were based on Luke (2025).

The efficiency of utilisation of ME for milk production (k_l) was calculated using the following equation:

$$k_l = \frac{ECM \times 3.14}{corrected\ ME\ intake - ME\ for\ maintenance \pm ME\ for\ body\ weight\ change}$$

The MP balance was calculated according to the following equation:

$$MP\ balance,\ \frac{g}{day} = MP\ intake - (MP\ for\ maintenance + MP\ for\ milk\ production \pm MP\ for\ body\ weigth\ change)$$

The nitrogen use efficiency in milk production (NUE) was calculated as follows:

$$NUE = \frac{Nexcreted\ in\ milk,\ \frac{g}{day}}{Nintake,\ \frac{g}{day}}$$

The experimental setup for both sub-experiments was a random block design with repeated measurements, wherein the block factor was as similar as possible between the pairs of cows. Data were analysed separately for EL and LL experiments using SAS MIXED procedure (version 9.4; SAS Institute Inc., Cary, NC, USA). The statistical model included the diet, lactation week/experimental week and the pair as fixed variables and the animal as a random variable for the variables feed and nutrient intake, milk production, milk production efficiency, and BW. The diet × lactation week/experimental week interaction was also included in the model. For LL group, the pre-experimental milk yield, ECM yield and BW were also included in the model as a covariate factor for them. The repeated factor was the lactation week for EL and the experimental week for LL. The BWC was determined through the calculation of individual bodyweight regressions. Slopes derived from these regressions were then employed to ascertain the BWC during the early and late lactation periods. The statistical model included the diet and the pair as fixed variables.

For BCS and blood analyses, the statistical model included the diet, measurement time and the pair as fixed variable and measurement time was used as a repeated factor. The diet × measurement time interaction was also included in the model.

The normality and homoscedasticity of the residuals were examined by visual evaluation for assessment and assurance of model fit and normality of the data. Assumptions for normality were met for all variables except for BHBA and NEFA, which were log-transformed to normalise the distribution.

Significance of fixed effects was declared at $P \leq 0.05$ and tendencies at $0.05 < P \leq 0.1$.

3. Results

During early lactation, no differences were found in total DM intake between the dietary treatments ($P = 0.144$). However, the EL-45 treatment exhibited a numerically higher total DM intake, which was almost 1 kg greater than the EL-35 treatment (Table 3). Consequently, the ME intake was greater for EL-45 than for EL-35 ($P < 0.05$). Higher protein balance in the rumen was observed when EL-35 was fed ($P < 0.001$).

In late lactation, no statistically significant differences were found in the total DM intake between the dietary treatments ($P = 0.122$), yet the LL-35 diet resulted in numerically higher total DM and ME intake. Higher protein balance in the rumen was observed when LL-27 was fed ($P < 0.001$).

The ECM yield of EL-45 was higher in comparison to EL-35 ($P = 0.004$) (Table 4), while no statistically significant difference was noted in milk yield between dietary treatments ($P = 0.156$), although the numerical difference in milk yield between the diets was 1.9 kg. The EL-45 diet resulted in higher fat and protein production compared to EL-35 ($P = 0.002$ and $P = 0.027$, respectively). No differences in milk composition were observed during early lactation.

During the late lactation there was a tendency ($P = 0.057$) for the milk and ECM yield of LL-35 to be higher compared to LL-27 ($P = 0.062$ and $P = 0.098$, respectively).

In early lactation, no significant differences were identified in feed efficiency, as indicated by the ratio of kg ECM to kg DM intake or MJ ME to kg ECM ($P = 0.323$ and $P = 0.724$, respectively) (Table 5). Furthermore, the efficiency of ME utilisation for milk production (k_l) was found to be similar between the dietary treatments ($P = 0.272$). Numerical comparison across lactation stages showed that k_l

Table 3
Feed and nutrient intake of dairy cows offered the experimental diets during early and late lactation.

	EL-35[1]	EL-45[2]	SEM[3]	*p*-value	LL-27[4]	LL-35[5]	SEM	*p*-value
Dry matter (DM) intake, kg/day								
Silage	13.9	12.2	0.28	< 0.001	15.4	14.6	0.38	0.144
Concentrate	7.0	9.6	0.17	-	5.7	7.6	0.16	-
Total	20.9	21.8	0.44	0.144	21.1	22.2	0.53	0.122
Daily nutrient intake								
Crude protein, g	3543	3568	74.3	0.814	3630	3733	89.8	0.418
Neutral detergent fibre, g	9637	9396	191.9	0.377	10219	10293	260.8	0.845
Metabolisable energy, MJ	240	255	5.1	0.037	235	251	5.9	0.054
Corrected metabolisable energy[6], MJ	226	238	4.4	0.060	223	236	5.1	0.103
Metabolizable protein, g	1972	2070	41.9	0.101	1980	2097	49.7	0.099
Protein balance in the rumen, g	666	508	12.5	< 0.001	784	692	18.0	< 0.001

[1] EL-35 = Early lactation diet with 35 % of concentrate in the diet
[2] EL-45 = Early lactation diet with 45 % of concentrate in the diet
[3] SEM = Standard error of the mean
[4] LL-27 = Late lactation diet with 27 % of concentrate in the diet
[5] LL-35 = Late lactation diet with 35 % of concentrate in the diet
[6] Metabolisable energy intake was calculated according to Luke (2025) considering the effects of diet composition and feed intake level.

Table 4
Milk production of dairy cows fed the experimental diets during early and late lactation.

	EL-35[1]	EL-45[2]	SEM[3]	*p*-value	LL-27[4]	LL-35[5]	SEM	*p*-value
Production per day								
Milk, kg	35.9	37.8	0.96	0.156	26.5	28.0	0.60	0.062
Energy corrected milk, kg	40.2	43.6	0.81	0.004	31.2	32.9	0.74	0.098
Fat, g	1798	1993	43.0	0.002	1388	1479	64.9	0.322
Protein, g	1320	1427	33.7	0.027	1075	1115	31.2	0.393
Lactose, g	1669	1776	45.9	0.103	1075	1115	31.2	0.393
Milk composition, g/kg								
Fat	49.0	51.2	1.28	0.227	51.6	53.3	1.98	0.547
Protein	35.8	36.5	0.58	0.380	40.0	40.1	0.84	0.885
Lactose	45.2	45.1	0.35	0.911	43.5	44.7	0.45	0.068
Urea, mg/L	1828	158.6	15.0	0.257	254.6	248.6	15.0	0.778
Fat-to-protein ratio	1.37	1.41	0.039	0.502	1.29	1.33	0.035	0.466

[1] EL-35 = Early lactation diet with 35 % of concentrate in the diet
[2] EL-45 = Early lactation diet with 45 % of concentrate in the diet
[3] SEM = Standard error of the mean
[4] LL-27 = Late lactation diet with 27 % of concentrate in the diet
[5] LL-35 = Late lactation diet with 35 % of concentrate in the diet

Table 5
Efficiency of milk production of dairy cows fed the experimental diets during early and late lactation.

	EL-35[1]	EL-45[2]	SEM[3]	*p*-value	LL-27[4]	LL-35[5]	SEM	*p*-value
Kg energy corrected milk (ECM)/kg dry matter intake	1.94	2.01	0.041	0.323	1.50	1.50	0.027	0.983
MJ metabolizable energy (ME)/kg ECM	4.27	4.35	0.008	0.548	5.24	5.49	0.086	0.049
Corrected ME[6], MJ/kg ECM	3.90	3.95	0.086	0.336	4.87	5.04	0.082	0.162
ME balance, ME MJ/day	-36	-36	4.1	0.929	3	11	2.7	0.039
ME balance, ME MJ/day with BWC[7]	-18	-13	3.4	0.286	4	4	3.9	0.942
ME balance, ME MJ/day (corrected)	-50	-53	3.7	0.657	-9	-4	2.9	0.238
ME balance, ME MJ/day (corrected) with BWC	-32	-30	3.2	0.672	-8	-11	3.6	0.580
Efficiency of ME utilisation for milk production, k_l	0.817	0.805	0.0185	0.656	0.646	0.627	0.0106	0.206
Efficiency of ME utilisation for milk production with BWC, k_l	0.724	0.708	0.0105	0.272	0.646	0.651	0.0174	0.855
Body weight, kg	692	654	14.1	0.06	679	691	4.5	0.062
Body weight change, kg/day	-0.649	-0.809	0.1188	0.364	-0.068	0.181	0.0821	0.058
Body condition score	3.43	3.36	0.072	0.557	3.3	3.4	0.10	0.712
Body condition score change[8]	-0.40	-0.48	0.085	< 0.001	-0.02	0.15	0.108	0.142
Metabolizable protein balance, g/day	-290.0	-299.5	39.10	0.879	-79.7	-33.2	18.42	0.077
Nitrogen use efficiency, g milk N output/g feed N intake	0.362	0.385	0.0084	0.050	0.291	0.294	0.0037	0.551

[1] EL-35 = Early lactation diet with 35 % of concentrate in the diet
[2] EL-45 = Early lactation diet with 45 % of concentrate in the diet
[3] SEM = Standard error of the mean
[4] LL-27 = Late lactation diet with 27 % of concentrate in the diet
[5] LL-35 = Late lactation diet with 35 % of concentrate in the diet
[6] Metabolisable energy intake was calculated according to Luke (2025) considering the effects of diet composition and feed intake level.
[7] Body weight change
[8] Body condition score change = Change between the start of the experiment and the end of the experiment

was higher in early lactation; however, the difference diminished when BWC was also taken into account. The NUE was higher when EL-45 diet was fed ($P = 0.050$). The ME balance (MJ/day) was negative for both treatments and did not differ between the diets ($P > 0.05$).

During late lactation, no significant differences were observed between LL-27 and LL-35 diets in terms of feed efficiency presented as kg ECM/kg DM intake ($P = 0.892$) or k_l ($P = 0.129$). However, MJ ME/kg ECM was lower in the LL-27 diet ($P = 0.049$) (Table 5).

Table 6
Non-esterified fatty acids (NEFA) and beta-hydroxybutyrate (BHB) in plasma of early lactation dairy cows fed the experimental diets.

	EL-35[1]	EL-45[2]	SEM[3]	*p*-value
In plasma, mmol/l				
NEFA	0.59	0.45	0.067	0.294
BHB	1.40	1.42	0.212	0.876

[1] EL-35 = Early lactation diet with 35 % of concentrate in the diet
[2] EL-45 = Early lactation diet with 45 % of concentrate in the diet
[3] SEM = Standard error of the mean

The ME balance (uncorrected ME MJ/day) was marginally more negative in LL-27 than LL-35 diet ($P = 0.049$).

The metabolisable protein balance (g/day) tended to be more negative with the LL-27 diet compared to the LL-35 diet ($P = 0.077$).

During early lactation, the cows lost approximately 0.729 kg/day of BW but no significant difference in BWC was observed between treatments ($P = 0.364$) (Table 5). Nevertheless, the cows in EL-45 had a greater change in BCS during the experiment, with a reduction of 0.075 units of BCS per 8 weeks ($P < 0.001$).

During late lactation, there was a tendency for the LL-35 cows to gain more BW ($P = 0.058$) compared to the LL-27 cows, who demonstrated a slight negative change in BW (Table 5). No differences were observed between dietary treatments in terms of BCS change ($P = 0.164$).

No differences in plasma BHBA concentrations were observed between treatments during early lactation ($P = 0.876$; Table 6). There was a tendency ($P = 0.072$) for an interaction of BHBA and measurement week, indicating that during the first lactation week, BHBA was lower in the EL-35 group, but higher in the sixth lactation week. The EL-35 cows had numerically higher plasma NEFA concentrations, but no statistical significance was identified ($P = 0.294$).

4. Discussion

4.1. Diets and feed intake

The aim of this experiment was to compare two concentrate feeding strategies to improve milk yield per additional kilogram of concentrate supplemented within an intensive grass silage-based milk production system. Improved efficiency can be achieved by allocating concentrates to the most responsive cows. This strategy should be implemented in the most cost-effective and practical way possible; therefore, we used two sub-experiments (early and late lactation feeding experiments) to evaluate the system.

In two sub-experiments, a constant concentrate level with 35 % concentrate in the diet during early and late lactation was compared with a strategy using higher concentrate proportion (45 %) in early lactation diet and lower concentrate proportion (27 %) during late lactation. Diets were formulated so that the MP level of the diets was fixed and not confounded with the experimental treatments. Higher concentrate proportion used in the early lactation (45 %) was close to Finnish national average level, which was 46 % in 2024 (Korhonen, 2025).

It could be argued that this experiment should have included mid-lactation measurements, as concentrate feeding strategies should ideally be evaluated across the entire lactation period. However, several feeding experiments have been conducted with mid-lactating dairy cows and the production responses to concentrate feeding during that period are well known (Huhtanen and Nousiainen, 2012). In these studies, no significant interaction was found between production level and the proportion of concentrate feed, indicating that adjusting the forage-to-concentrate ratio during mid-lactation offers no clear advantage. In contrast, fewer studies have focused on early and late lactation stages in relation to concentrate feeding levels and production responses. This gap in the literature was the primary rationale for the chosen experimental design.

In this experiment, higher concentrate supplementation systematically increased total DM intake by 0.9 kg in early and 1.1 kg in late lactation, respectively, which is in line with previous studies (Huhtanen et al., 2008; Sairanen et al., 2022). Lack of statistical significance is most likely reflecting relatively small sample size. Higher DM intake resulted in a tendency for greater ME and MP intake at higher concentrate feeding levels.

In both early and late lactation, the silage DM intake was lower at higher concentrate feeding level, which can be attributed to the effect of substitution rate (SR, kg decrease in silage DM intake per each kg increase in concentrate DM intake). The SR is typically affected by the level of concentrate and the quality of the silage (Huhtanen et al., 2008). In the meta-analysis conducted by Huhtanen et al. (2008), the average SR was 0.47. In the present study, the mean SR (0.65 in early lactation and 0.40 in late lactation) aligns with previous findings, indicating that SR increases with higher levels of concentrate supplementation and is also associated with the energy status of cows (Faverdin et al., 1991; Randby et al., 2012; Sairanen et al., 2022).

4.2. Milk yield and feed efficiency

Increasing the level of concentrate supplementation improves milk yield (e.g. Randby et al., 2012; Sairanen et al., 2022), as also observed in both sub-experiments of the present study. The lack of statistical significance in EL milk yield and LL milk and ECM yields is likely attributable to the limited number of animals included in the study.

Higher concentrate feeding slightly increased both protein and fat concentration in early and late lactation resulting in higher protein and fat yields in early lactating cows in line with earlier findings (Huhtanen and Rinne, 2007). Numerically this phenomenon was also observed in late lactating cows. Milk fat concentration is more variable in response to concentrate feeding compared to milk protein (Huhtanen and Rinne, 2007) but milk fat reduction is usually observed at much higher concentrate supplementation levels (Bauman and Griinari, 2003; Huhtanen and Rinne, 2007).

No differences were observed between early and late lactation diets in terms of milk urea concentration. However, milk urea concentration was surprisingly low in early lactation relative to the dietary crude protein level. Consequently, it can be hypothesised that the intake of MP was not a limiting factor for the milk yield, as the protein level in the milk remained within the typical range (Korhonen, 2025).

As hypothesised, the average ECM production response (kg ECM/kg supplementary concentrate DM) was numerically higher in early lactation compared to late lactation (1.3 and 0.9, respectively). For milk, the difference in response was however negligible (0.74 and 0.80, respectively). The observed difference in the response of ECM production is due to differences in energy partitioning between different lactation stages (Kirkland and Gordon, 2001), and is consistent with earlier findings (Coulon and Rémond, 1991; Kirkland and Gordon, 2001). During the early stages of lactation, the energy provided by the diet is primarily allocated towards milk production (Kirkland and Gordon, 2001), as the main biological function is focused on ensuring the survival of the offspring. It can be hypothesised that breeding goals aiming at increasing milk yields have also contributed to this mechanism, as genetically superior dairy cows exhibit a greater capacity to allocate a higher proportion of their energy reserves towards milk production compared to medium-merit cows (Ferris et al., 1999; Yan et al., 2006). In contrast, during late lactation the ME intake is allocated more to body tissues (Kirkland and Gordon, 2001), which was also observed in this experiment.

In terms of feed efficiency, no differences were observed between the diets in early lactation, except that NUE was higher in the high concentrate diet. This was a consequence of the higher CP in the low concentrate diet, which was also reflected in higher milk urea concentration when LL was fed. Energy conversion efficiency (MJ ME/kg ECM) in early lactation was relatively high compared to the energy requirement value based on the Finnish feed evaluation system (4.31 vs 5.15; Luke, 2025) and compared to late lactation (average 5.37). Accordingly, production response to increased energy intake (kg ECM/MJ ME) was higher during early lactation compared to late lactation (0.23 vs 0.11). During late lactation, milk yield decreases more than DM intake, which is reflected in apparent feed utilisation (Mäntysaari et al., 2003, 2004). In early lactation, apparent feed utilisation for milk production is higher, as the cow also mobilises energy from body tissues for milk synthesis, as described by e.g. Ormston et al. (2025).

In late lactation, cows with a lower concentrate intake produced milk more efficiently than cows with a higher concentrate intake in terms of MJ ME/kg ECM. A likely explanation for this is that on the high concentrate diet, the cows directed some of the concentrate feed energy towards body deposition and had a higher BWC.

4.3. Energy balance and ketosis

In practice, supplementary concentrate feeding is commonly used with the aim to improve the energy balance of dairy cows. However, as hypothesised, and demonstrated by this and previous studies (Ferris et al., 1999; Sairanen et al., 2013), concentrate supplementation does not always enhance the energy balance of early lactating cows. Modern dairy cows, bred for high milk yields, have a high yield potential, and milk yield is constrained typically by energy availability. When dietary energy intake increases, milk yield may rise accordingly, as genetic potential is not the limiting factor. Moreover, the additional energy from concentrates tends to be directed towards milk production rather than replenishing body tissue reserves.

In contrary to early lactation, during late lactation the feed energy is increasingly allocated to tissue stores (Kirkland and Gordon, 2001). This was also observed in this experiment demonstrated by negative BWC in early lactation and positive BWC in late lactation, which was in line with our hypothesis. Interestingly though, low concentrate diet during late lactation resulted in slightly negative BWC. Excessive BW gain during late lactation is generally considered undesirable from a health perspective, particularly due to its association with an increased risk of metabolic disorders such as hyperketonemia (Rathbun et al., 2017) after calving. In this context, the lower proportion of concentrate in the late lactation may be regarded as a beneficial outcome, potentially contributing to improved metabolic stability during the following lactation period (Kokkonen et al., 2000).

Plasma concentrations of NEFA and BHBA, both widely recognized biomarkers of body reserve mobilization during negative energy balance in early lactation, did not differ significantly between the dietary treatments. These findings support earlier observations within this study, suggesting that differences in energy balance and tissue mobilisation between cows fed varying concentrate levels were minimal.

Peak plasma NEFA and BHBA concentrations were observed during the third week of lactation, consistent with previous studies indicating that maximal lipolytic activity typically occurs within the first month postpartum (Ospina et al., 2010). Although mean NEFA levels were numerically higher in the lower concentrate group, substantial individual variation was observed, particularly within the low concentrate treatment. This variability is consistent with earlier findings (Kessel et al., 2008) highlighting the influence of individual metabolic capacity on lipolysis and ketogenesis.

A plasma NEFA concentration of ≥ 0.7 mmol/l is commonly used as a threshold for indicating a severe negative energy balance (Adewuyi et al., 2005). In the present experiment, six cows exceeded this threshold during the third week of lactation. By the sixth week, only three cows remained above this level, suggesting an improvement in energy balance as lactation progressed. During negative energy balance periods, increased mobilisation of adipose tissue enhances hepatic ketogenesis. A blood BHBA concentration of ≥ 1.2 mmol/l is frequently used as a threshold for subclinical ketosis (Suthar et al., 2013). In this study, more than half of the cows exceeded this threshold during both the third and sixth weeks of lactation.

Clinical ketosis, defined as BHBA > 3.0 mmol/l (McArt et al., 2012), was observed in one cow during the third week and in two cows during the sixth week. Despite these elevated values, no clinical signs of ketosis were observed, and none of the animals required treatment during the experiment. Although traditionally considered a metabolic disorder, ketosis in dairy cows may also represent a physiological adaptation to early lactation. Recent research suggests (Rico and Barrientos-Blanco, 2024) that moderate hyperketonemia can occur without adverse health effects and may even offer metabolic benefits. This highlights the need for a more nuanced understanding of ketosis, distinguishing pathological conditions from potentially beneficial ketone metabolism.

4.4. Economic evaluation of concentrate feeding strategies

Concentrate feeding in dairy production encompasses both economic efficiency and animal welfare considerations on top of biological conversion efficiency. From an economic standpoint, the primary objective is to maximise milk yield relative to feed investment. In the current feeding experiment, we analysed the economic viability of concentrate feeding during the early and late lactation periods with low and high dietary concentrate levels. The used milk price, with fixed milk composition, was 63/61 cents per kg for low and high concentrate levels during early lactation, and 65/66 cents per kg during late lactation, respectively. The feed cost per kilogram milk was 12 cents in early lactation and 15 cents in late lactation, respectively.

Given these milk and feed price ratios, the price of concentrate feed would need to more than quadruplicate (>75 cents/kg DM) before a low concentrate feeding strategy becomes more profitable in early lactation. During late lactation, the milk production response to concentrate feeding is smaller, making the low concentrate feeding strategy more profitable at a lower concentrate price (45 cents/kg DM) compared to early lactation.

The additional income per kilogram of concentrate feed is significantly lower during the late lactation period compared to the early lactation period. Therefore, from economical point of view, it is advisable to target the higher use of concentrates for early lactation and reduce the use in late lactation. As discussed earlier, during the late lactation period the adverse effects of cows gaining excessive weight may pose a greater health risk compared to the additional income derived from concentrate feed.

However, economic evaluations are highly dependent on the prevailing milk and feed prices which are volatile over times. Decisions regarding feeding strategies should always be based on farm-specific cost calculations for both forage and concentrate feeds to achieve the economically optimal solution and adjusted regularly when milk and feed prices change. A grass silage-based dairy production strategy requires additional subsidies if it is to become more widespread for environmental reasons.

5. Conclusions

According to our results, it is more reasonable to use a higher concentrate proportion in early lactation diet and a lower proportion in the late lactation if the aim is to reduce overall concentrate use in dairy production. Higher concentrate feeding did not improve energy balance of early lactating cows, or their energy status based on plasma concentration markers, yet key parameters were not weaker compared to a low concentrate diet. Due to higher milk yield response and economic returns, it is more advantageous to target higher concentrate feeding during the early lactation. In addition, the lower concentrate feed during the late lactation limited body weight increase, reducing the risk of excessive fat deposition. This approach provides benefits for subsequent calving and the early stages of the next lactation but requires grouping animals in TMR feeding or adjusting the concentrate feeding individually in PMR or separate feeding.

Data statement

The original data is available from the corresponding author upon request.

CRediT authorship contribution statement

Sari Kajava: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marketta Rinne:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Auvo Sairanen:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Microsoft Copilot in order to check the grammar, spelling and to improve the readability of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of Competing Interest

This statement applies to the manuscript "Evaluation of concentrate feeding strategies in an intensive grass silage-based dairy production system" by Sari Kajava, Marketta Rinne and Auvo Sairanen submitted to Animal Feed Science and Technology. All authors disclose no financial and personal relationships with other people or organizations that could inappropriately influence or bias this work.

Acknowledgements

We gratefully acknowledge the funding received from the European Agricultural Fund for Rural Development for HiiliMaito project.

References

Adewuyi, A.A., Gruys, E., van Eerdenburg, F.J.C.M., 2005. Non esterified fatty acids (NEFA) in dairy cattle. A review. Vet. Q. 27, 117–126. https://doi.org/10.1080/01652176.2005.9695192.

Bauman, D.E., Griinari, J.M., 2003. Nutritional regulation of milk fat synthesis. Annu. Rev. Nutr. https://doi.org/10.1146/annurev.nutr.23.011702.073408.

Bengtsson, J., Bullock, J.M., Egoh, B., Everson, C., Everson, T., O'Connor, T., O'Farrell, P.J., Smith, H.G., Lindborg, R., 2019. Grasslands—more important for ecosystem services than you might think. Ecosphere 10, e02582. https://doi.org/10.1002/ecs2.2582.

Berry, D.P., Veerkamp, R.F., Dillon, P., 2006. Phenotypic profiles for body weight, body condition score, energy intake, and energy balance across different parities and concentrate feeding levels. Livest. Sci. 104, 1–12. https://doi.org/10.1016/j.livsci.2006.02.012.

Coulon, J.B., Rémond, B., 1991. Variations in milk output and milk protein content in response to the level of energy supply to the dairy cow: A review. Livest. Prod. Sci. 29, 31–47. https://doi.org/10.1016/0301-6226(91)90118-A.

Everson, R.A., Jorgensen, N.A., Crowley, J.W., Jensen, E.L., Barrington, G.P., 1976. Input-output of dairy cows fed a complete ration of a constant or variable forage-to-grain Ratio1. J. Dairy Sci. 59, 1776–1787. https://doi.org/10.3168/jds.S0022-0302(76)84437-2.

Faverdin, P., Dulphy, J.P., Coulon, J.B., Vérité, R., Garel, J.P., Rouel, J., Marquis, B., 1991. Substitution of roughage by concentrates for dairy cows. Livest. Prod. Sci. 27, 137–156. https://doi.org/10.1016/0301-6226(91)90092-5.

Ferris, C.P., Gordon, F.J., Patterson, D.C., Mayne, C.S., Kilpatrick, D.J., 1999. The influence of dairy cow genetic merit on the direct and residual response to level of concentrate supplementation. J. Agric. Sci. 132, 467–481. https://doi.org/10.1017/S0021859699006474.

Haacker, K., Block, H.J., Weissbach, F., 1983. Zur kolorimetrischen Milchsäurebestimmung in Silagen mit p-Hydroxydiphenyl. [On the colorimetric determination of lactic acid in silages with p-hydroxydiphenyl]. Arch. F. üR. Tiere ährung 505–512.

Huhtanen, P., Nousiainen, J., 2012. Production responses of lactating dairy cows fed silage-based diets to changes in nutrient supply. Livest. Sci. 148, 146–158. https://doi.org/10.1016/j.livsci.2012.05.023.

Huhtanen, P., Rinne, M., 2007. Effects of increasing the milk yield of dairy cows on milk composition. J. Anim. Feed Sci. 16, 42–58. https://doi.org/10.22358/jafs/74111/2007.

Huhtanen, P., Nousiainen, J., Rinne, M., 2006. Recent developments in forage evaluation with special reference to practical applications. AFSci 15, 293–323. https://doi.org/10.2137/145960606779216317.

Huhtanen, P., Rinne, M., Nousiainen, J., 2007. Evaluation of the factors affecting silage intake of dairy cows: a revision of the relative silage dry-matter intake index. Animal 1, 758–770. https://doi.org/10.1017/S175173110773673X.

Huhtanen, P., Rinne, M., Nousiainen, J., 2008. Evaluation of concentrate factors affecting silage intake of dairy cows: a development of the relative total diet intake index. Animal 2, 942–953. https://doi.org/10.1017/S1751731108001924.

Huhtanen, P.J., Blauwiekel, R., Saastamoinen, I., 1998. Effects of intraruminal infusions of propionate and butyrate with two different protein supplements on milk production and blood metabolites in dairy cows receiving grass silage based diet. J. Sci. Food Agric. 213–222.

Huida, L., Väätäinen, H., Lampila, M., 1986. Comparison of dry matter contents in grass silage as determined by oven drying and gas chromatographic water analysis. Ann. Agric. Fenn. 215–230.

Kessel, S., Stroehl, M., Meyer, H.H.D., Hiss, S., Sauerwein, H., Schwarz, F.J., Bruckmaier, R.M., 2008. Individual variability in physiological adaptation to metabolic stress during early lactation in dairy cows kept under equal conditions. J. Anim. Sci. 86, 2903–2912. https://doi.org/10.2527/jas.2008-1016.

Keys, J.E., Pearson, R.E., Hooven, N.W., Tyrrell, H.F., Bodoh, G.W., 1983. Individual versus group feeding of constant versus variable forage:concentrate of total mixed rations through two lactations and intervening dry Period1. J. Dairy Sci. 66, 1076–1083. https://doi.org/10.3168/jds.S0022-0302(83)81904-3.

Kirkland, R.M., Gordon, F.J., 2001. The effects of stage of lactation on the partitioning of, and responses to changes in, metabolisable energy intake in lactating dairy cows. Livest. Prod. Sci. 72, 213–224. https://doi.org/10.1016/S0301-6226(01)00220-2.

Kokkonen, T., Tesfa, A., Tuori, M., Hissa, K., Jukola, E., Syrjälä-Qvist, L., 2000. Effects of early lactation concentrate level and glucogenic feed on feed intake, milk production and energy metabolism in dairy cows and heifers. J. Anim. Feed Sci. 9, 563–583. https://doi.org/10.22358/jafs/68083/2000.

Kokkonen, T., Taponen, J., Anttila, T., Syrjälä-Qvist, L., Delavaud, C., Chilliard, Y., Tuori, M., Tesfa, A.T., 2005. Effect of body fatness and glucogenic supplement on lipid and protein mobilization and plasma leptin in dairy cows. J. Dairy Sci. 88, 1127–1141. https://doi.org/10.3168/jds.S0022-0302(05)72779-X.

Korhonen, I., 2025. Ruokinnan tunnusluvut Vuode.. 2024 [Key Indic. Feed. 2024].

Luke, 2025. Feed Tables and Nutrient Requirements. Natural Resources Institute Finland, Jokioinen, Finland.

Mäntysaari, P., Nousiainen, J., Huhtanen, P., 2003. The effect of constant or variable forage to concentrate ratio in total mixed ration on performance of primiparous dairy cows. Livest. Prod. Sci. 82, 27–37. https://doi.org/10.1016/S0301-6226(03)00007-1.

Mäntysaari, P., Huhtanen, P., Nousiainen, J., Virkki, M., 2004. The effect of concentrate crude protein content and feeding strategy of total mixed ration on performance of primiparous dairy cows. Livest. Prod. Sci. 85, 223–233. https://doi.org/10.1016/S0301-6226(03)00131-3.

McArt, J.A.A., Nydam, D.V., Oetzel, G.R., 2012. Epidemiology of subclinical ketosis in early lactation dairy cattle. J. Dairy Sci. 95, 5056–5066. https://doi.org/10.3168/jds.2012-5443.

McCullough, H., 1967. The determination of ammonia in whole blood by direct colorimetric method. Clin. Chim. Acta 297–304. https://doi.org/10.1016/0009-8981(67)90133-7.

Miller, R.H., Hooven, N.W., Creegan, M.E., 1969. Weight changes in lactating holstein cows. J. Dairy Sci. 52, 90–94. https://doi.org/10.3168/jds.S0022-0302(69)86507-0.

Nousiainen, J., Rinne, M., Hellämäki, M., Huhtanen, P., 2003. Prediction of the digestibility of the primary growth of grass silages harvested at different stages of maturity from chemical composition and pepsin-cellulase solubility. Anim. Feed Sci. Technol. 97–111.

Ormston, S., Yan, T., Chen, X., Gordon, A.W., Theodoridou, K., Huws, S., Stergiadis, S., 2025. Efficiency of feed and energy use in primiparous and multiparous dairy cows fed contrasting dietary protein concentrations across lactation. animal 19, 101426. https://doi.org/10.1016/j.animal.2025.101426.

Ospina, P.A., Nydam, D.V., Stokol, T., Overton, T.R., 2010. Association between the proportion of sampled transition cows with increased nonesterified fatty acids and β-hydroxybutyrate and disease incidence, pregnancy rate, and milk production at the herd level. J. Dairy Sci. 93, 3595–3601. https://doi.org/10.3168/jds.2010-3074.

Randby, Å.T., Weisbjerg, M.R., Nørgaard, P., Heringstad, B., 2012. Early lactation feed intake and milk yield responses of dairy cows offered grass silages harvested at early maturity stages. J. Dairy Sci. 95, 304–317. https://doi.org/10.3168/jds.2011-4454.

Rathbun, F.M., Pralle, R.S., Bertics, S.J., Armentano, L.E., Cho, K., Do, C., Weigel, K.A., White, H.M., 2017. Relationships between body condition score change, prior mid-lactation phenotypic residual feed intake, and hyperketonemia onset in transition dairy cows. J. Dairy Sci. 100, 3685–3696. https://doi.org/10.3168/jds.2016-12085.

Rico, J.E., Barrientos-Blanco, M.A., 2024. Invited review: Ketone biology: the shifting paradigm of ketones and ketosis in the dairy cow. J. Dairy Sci. https://doi.org/10.3168/jds.2023-23904.

Roche, J.R., Friggens, N.C., Kay, J.K., Fisher, M.W., Stafford, K.J., Berry, D.P., 2009. Invited review: Body condition score and its association with dairy cow productivity, health, and welfare. J. Dairy Sci. 92, 5769–5801. https://doi.org/10.3168/jds.2009-2431.

Rukkwamsuk, T., Kruip, T.A.M., Wensing, T., 1999. Relationship between overfeeding and overconditioning in the dry period and the problems of high producing dairy cows during the postparturient period. Vet. Q. 21, 71–77. https://doi.org/10.1080/01652176.1999.9694997.

Saarinen, M., Kaljonen, M., Niemi, J., Antikainen, R., Hakala, K., Hartikainen, H., Heikkinen, J., Joensuu, K., Lehtonen, H., Mattila, T., Nisonen, S., Ketoja, E., Knuuttila, M., Regina, K., Rikkonen, P., Seppälä, J., Varho, J., 2019. Ruokavaliomuutoksen vaikutukset ja muutosta tukevat politiikkayhdistelmät: RuokaMinimi-hankkeen loppuraportti [Effects of Dietary Change and Policy Combinations Supporting Change: Final Report of the FoodMinimum project].

Sairanen, A., Huhtanen, P., 2024. Variation in individual milk production responses to supplementary protein feeding with two types of forages. Livest. Sci. 280, 105394. https://doi.org/10.1016/j.livsci.2023.105394.

Sairanen, A., Juutinen, E., Rinne, M., Zollitsch, W., 2013. Sustainable milk production using low concentrate input. in: 17th Symposium of the European Grassland Federation. Agricultural University of Iceland, p. 41.

Sairanen, A., Juutinen, E., Rinne, M., 2022. The effect of grass silage harvesting strategy and concentrate level on feed intake, diet digestibility and milk production of dairy cows. AFSci 31 160174. https://doi.org/10.23986/afsci.113471.

Sairanen, A., Kajava, S., Hietala, S., 2024. Effect of forage-to-concentrate ratio in dairy cow diets on estimated milk carbon footprint. Grassland Science Europe Presented EGF Grassland Science Europe 169–172.

Sjaunja, L.O., Baevre, L., Junkkarinen, L., Pedersen, J., Setälä, J., 1990. A Nordic proposal for an energy corrected milk (ECM) formula. Proceedings of the 27th session of International Committee of Recording and Productivity of Milk Animal.
Somogyi, M., 1945. A new reagent for the determination of sugars. J. Biol. Chem. 61–68.
Steinshamn, H., Thuen, E., 2008. White or red clover-grass silage in organic dairy milk production: grassland productivity and milk production responses with different levels of concentrate. Livest. Sci. 119, 202–215. https://doi.org/10.1016/j.livsci.2008.04.004.
Suthar, V.S., Canelas-Raposo, J., Deniz, A., Heuwieser, W., 2013. Prevalence of subclinical ketosis and relationships with postpartum diseases in European dairy cows. J. Dairy Sci. 96, 2925–2938. https://doi.org/10.3168/jds.2012-6035.
Van Soest, P.J., Robertson, J.B., Lewis, B.A., 1991. Methods for dietary fibre, neutral detergent fibre and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 3583–3597. https://doi.org/10.3168/jds.S0022-0302(91)78551-2.
Yan, T., Mayne, C.S., Keady, T.W.J., Agnew, R.E., 2006. Effects of dairy cow genotype with two planes of nutrition on energy partitioning between milk and body tissue. J. Dairy Sci. 89, 1031–1042. https://doi.org/10.3168/jds.S0022-0302(06)72170-1.