ENERGY BALANCE AND PRODUCTION EFFICIENCY OF A FAMILY-BASED MIXED DAIRY SYSTEM

Antonio A. A. Chepluki
Federal University of Lavras, Agricultural Engineering Department, Campus, ZIP Code 37.200-900, Lavras, MG, Brazil

Alessandro Torres Campos
Federal University of Lavras, Agricultural Engineering Department, Campus, ZIP Code 37.200-900, Lavras, MG, Brazil

Roberto A. Braga
Federal University of Lavras, Automatic Department, Campus, ZIP Code 37.200-900, Lavras, MG, Brazil
Corresponding author: antonio.chepluki1@estudante.ufla.br

Abstract: While the energy use of intensive confinement models is widely documented, there is a lack of studies quantifying the energy performance of small-scale family systems that integrate pasture and on-farm silage. Therefore, this study analysed the energy flows of a family-based mixed dairy system in the subtropical region of Southern Brazil. Using a "cradle-to-farm-gate" approach over a one-year cycle, direct and indirect energy inputs were evaluated to determine specific energy consumption and energy productivity. The investigation monitored a herd of 16 lactating cows, yielding a commercial output of 134,171 kg of milk, with flows quantified across four processes: herd feeding, milking and cooling, sanitary management, and animal health. The system required 554.6 GJ year^{-1}, resulting in a specific energy consumption of 4.13 MJ kg^{-1} and an energy productivity of 0.242 kg MJ^{-1}. Herd feeding was the dominant energy-consuming process (87.2%), with commercial concentrate and mineral fertilisers accounting for 30.7% and 28.4% of total energy input, respectively. The findings identify commercial concentrate use and forage nutrient management as priorities for reducing energy demand. Agronomic strategies, including winter legumes and nutrient cycling, may contribute to reducing dependence on external energy inputs.

Keywords: Corn silage, Fossil dependency, Energy intensity, Nitrogen fertiliser, Smallholder.

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INTRODUCTION

Milk production plays a central role in the global food supply, but it raises growing concerns regarding its environmental impact and high demand for non-renewable resources. The livestock sector is a major consumer of direct energy, such as electricity and fossil fuels, and indirect energy embodied in agricultural inputs (Paris *et al.*, 2022). Recent global assessments indicate that feed production is the primary energy sink in dairy systems, often accounting for more than 75% of the total energy footprint due to the high energy cost of producing concentrates and forage (Shine *et al.*, 2020; Uçal *et al.*, 2023). Consequently, improving energy efficiency is not only an environmental imperative but also a strategy to reduce production costs and enhance the economic resilience of farms (Hercher-Pasteur *et al.*, 2020).

In Brazil, dairy farming is characterised by diverse production models, ranging from extensive grazing to highly intensive confinement systems. In the subtropical region of Southern Brazil, family-based smallholdings are predominant and often adopt mixed production systems (Balcão *et al.*, 2017). These systems typically combine pasture usage with on-farm silage production to bridge the forage gap during seasonal shortages. While pasture-based systems generally exhibit lower energy intensity compared to confinement models (Pagani *et al.*, 2016), the intensification of forage production introduces significant energy inputs. Studies by Müller *et al.* (2017) and Bernardes and Rêgo (2014) highlighted that

corn silage acts as the energetic engine of these systems but demands substantial agronomic inputs.

The energy demand of dairy farms is influenced by production intensity and the use of external inputs, particularly purchased feed and chemical fertilisers (Ramos *et al.*, 2014; Vahedi, 2024). The relationship between production intensity and resource use provides a relevant context for evaluating mixed dairy systems (Patiño; Bolívar-Vergara; Rosales, 2025).

A critical hotspot in mixed dairy systems is the use of nitrogenous fertilisers for silage production. Nitrogen is the most energy-intensive agricultural input (55.3–78.1 MJ kg^{-1}), and its excessive use can severely compromise the system's energy performance (Sefeedpari *et al.*, 2012; Komleh *et al.*, 2011). Romanelli and Milan (2005) and Azizpanah, Namdari, and Abed (2025) emphasised that fertilisers often represent the largest share of energy consumption in maize cultivation. Furthermore, the mechanisation required for silage production contributes to direct energy consumption in the form of diesel, although manual handling remains common in smaller Brazilian properties (Bernardes; Rêgo, 2014; Todde *et al.*, 2018a).

Despite the economic and social relevance of family-based mixed dairy systems in Southern Brazil, there is a gap in the literature regarding their specific energy performance. Most energy balance studies focus either on large-scale industrial systems (Todde *et al.*, 2018b) or general crop-livestock integration (Dhanapala *et al.*, 2023), often overlooking the specific trade-offs faced by smallholders who produce their own silage. Evaluating the energy flows of such systems is crucial for identifying sustainable practices that decrease reliance on external inputs (Luiz *et al.*, 2023; Maciel *et al.*, 2022).

Therefore, this study aimed to assess energy use and production performance in a family-based mixed dairy system in the subtropical region of Southern Brazil. The specific objectives were to: (i) quantify direct and indirect energy inputs across production processes; (ii) identify the main sources of energy consumption, particularly those associated with commercial concentrate and mineral fertilisation; and (iii) determine specific energy consumption and energy productivity, contextualising the results within the energy performance of dairy production systems reported in the literature.

MATERIAL AND METHODS

Study area and productive system

The study was conducted in a family dairy farm located in the city of Rebouças, Paraná, Brazil (25.6218° S, 50.6942° W), under a humid subtropical climate (Cfa, Köppen). The production system adopts a mixed base, combining corn cultivation for silage, pasture use, and supplementation with commercial concentrate and mineral salts. Land use is seasonal: from March to October, the 9.01 ha area used for silage is converted into winter pasture and added to 5.0 ha of permanent pasture, totalling 14.01 ha of grazing area. From October to March, the same 9.01 ha are occupied by corn for silage, while 5.0 ha remain under summer pasture.

The herd consists of 16 lactating cows, 8 dry cows, 5 heifers, and 6 calves, predominantly Holstein (70%) and Jersey-Holstein crossbreeds (30%). The annual milk production is of 134,263 litres, with an average productivity of 23 litres per lactating cow per day. Based on these productivity indicators and the management strategy adopted, the system is classified as medium intensive (or semi-intensive), representing the transition from subsistence to specialised dairying which is typical of the region (Balcão *et al.*, 2017).

The facilities cover 320 m^2, comprising milking and feeding parlors, storage, and a cooling room (Fig. 1). The infrastructure is built with concrete flooring and pre-cast concrete pillars supporting a metal roof structure covered with fibre-cement tiles. The walls are constructed of masonry without ceiling lining. The operation is carried out by two people, with an average daily workload of 4.5 hours. The data inventory was obtained through a structured questionnaire applied to the producer, production records, and field observations.

The milking system utilises a milking unit

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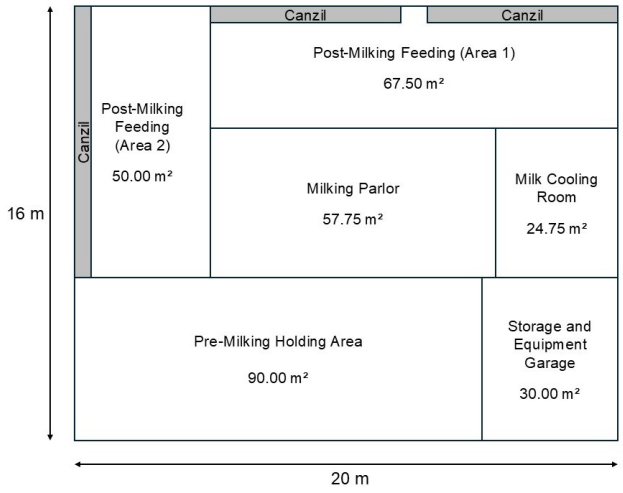


Figure 1: Floor plan sketch of the milking and feeding facilities.

driven by a 1.50 kW vacuum pump, operating for approximately 2.0 h day^{-1}. Milk storage and cooling are performed in a bulk tank equipped with a 1.12 kW compressor, which operates for 6.0 h day^{-1}. Sanitation routines involve the use of a 2.00 kW electric water heater (0.5 h day^{-1}) and a 1.50 kW high-pressure washer (0.25 h day^{-1}). Water supply is managed by pumps totalling 2.20 kW (1.5 h day^{-1} including cleaning and supply), and the lighting system consumes 0.80 kW for 8.0 h day^{-1} (combined milking and cleaning time).

Daily management begins in the paddock (Fig. 2a). Subsequently, the animals proceed to the holding area (Fig. 2b) for the first milking (Fig. 2c), after which they receive corn silage in the feed trough (Fig. 2d). They return to the paddock and, around 13:00 h, graze for approximately 1.5 hours to complement dry matter intake (Fig. 2e). Afterwards, the animals return to the paddock, undergo the second milking at dusk, and receive the evening feed in the trough. The night is spent in the paddock, with continuous access to water and rest until the cycle recommences.

Energy balance structure and system boundaries

The energy assessment adopted a "cradle-to-farm-gate" system boundary, encompassing all energy flows from the production of agricultural inputs to the storage of cooled milk at the farm (Shine *et al.*, 2020). Within these boundaries, the production system was stratified into four main operational processes to facilitate the identification of energy hotspots, following the process-based approach proposed by Ramos *et al.* (2014): (i) Herd feeding: subdivided into corn silage production (including soil preparation, planting, fertilisation, and harvesting) and pasture management; (ii) Milking and cooling: covering the electricity and labour required for milk extraction and preservation; (iii) Sanitary management: including cleaning routines of facilities and equipment; (iv) Animal health: accounting for veterinary treatments and medicines.

The assessment reported total annual energy demand (GJ year^{-1}) and used one kilogram of commercialised milk as the functional unit for specific energy consumption.

Calculation of energy inputs and performance indicators

The methodology adopted for the energy analysis was based on the flow and energy accounting model described by Patiño, Bolívar-Vergara, and Rosales (2025), which systematically quantifies the energy flows within the system boundaries considering three main components: inputs (direct and indirect), productive output (milk mass), and conversion factors.

Inputs were classified according to the criteria established by Patiño, Bolívar-Vergara, and Rosales (2025): (i) Direct energy input: includes energy sources consumed directly in on-farm operations, such as electricity, fossil fuels (diesel, gasoline, LPG), and human labour; (ii) Indirect energy input: encompasses the energy embodied in external inputs required for production, specifically categorised into animal supplementation (concentrates, forage, mineral salts) and pasture/crop management (fertilisers, seeds, and agrochemicals). Total energy input (E_{in}) was calculated by summing the annual quantities of each input multiplied by their respective energy coefficients (Eq. 1):



Figure 2: Routine and infrastructure of the dairy system: (a) cows resting in the paddock, with continuous access to water and shade; (b) holding area prior to milking; (c) animal positioned in the milking unit; (d) provision of corn silage in the feed trough with headlocks; (e) grazing in the field area; (f) trench-type surface silo for corn silage storage.

$$E_{in} = \sum(Q_j C_j) \quad (1)$$

where Q_j is the quantity of input j and C_j is the energy coefficient (MJ unit^{-1}).

To reflect the Brazilian electricity matrix in terms of primary energy, electrical consumption was converted using the national primary energy factor of 1.6 established by Kamimura *et al.* (2020), corresponding to 5.76 MJ kWh^{-1} (3.60 MJ kWh^{-1} $\times$ 1.6). For mineral fertilisation, the commercial fertiliser quantities reported by the producer were converted into active nutrient equivalents (N, P_2O_5, and K_2O) prior to applying the specific energy coefficients, following standard agricultural energy accounting procedures (Romanelli; Milan, 2005; Patiño; Bolívar-Vergara; Rosales, 2025). In corn silage cultivation (9.01 ha), the annual application consisted of 3,000 kg of NPK (08-20-20) and 3,750 kg of urea (45% N), corresponding to 1,927.5 kg of N, 600.0 kg of P_2O_5, and 600.0 kg of K_2O. In pasture management (14.01 ha), 1,500 kg of NPK (06-16-16) and 1,000 kg of urea (45% N) were applied, equivalent to 540.0 kg of N, 240.0 kg of P_2O_5, and 240.0 kg of K_2O.

Commercial concentrate was purchased as a ready-to-use formulated feed, with no on-farm formulation. The indirect energy coefficient of 6.30 MJ kg^{-1} reported by Patiño, Bolívar-Vergara, and Rosales (2025) was therefore adopted as a literature-based estimate.

The indirect energy embodied in agricultural machinery and equipment (manufacturing and maintenance) was estimated using a simplified approach proposed by Dalgaard, Halberg, and Porter (2001). Instead of detailed depreciation calculations based on mass and lifespan, this method assumes a linear relationship between the indirect energy of machinery and diesel consumption. Therefore, a specific coefficient

was applied to the fuel volume used in agricultural operations to estimate this input. The energy coefficients utilised for each input were obtained from the literature and are presented in Table 1.

The productive output was expressed as the annual mass of commercialised milk (M_{milk}), calculated from the recorded volume using an assumed density of 1.03 kg L^{-1}. Specific energy consumption (SEC) and energy productivity (EP) were calculated as follows:

$$SEC = \frac{E_{in}}{M_{milk}} \quad (2)$$

$$EP = \frac{M_{milk}}{E_{in}} \quad (3)$$

where E_{in} is the total annual energy input (MJ $year^{-1}$), M_{milk} is the annual commercialised milk mass (kg $year^{-1}$), SEC is expressed in MJ kg^{-1}, and EP in kg MJ^{-1}. These reciprocal indicators describe the energy demand per unit of commercial output and the mass of milk obtained per unit of accounted energy input, respectively.

RESULTS

Energy analysis by process

The energy demand for corn silage production is presented in Table 2. This subprocess required a total of 225,895.7 MJ $year^{-1}$. The analysis highlights the dominance of fertilisers, which accounted for 54.12% of the total energy input. Specifically, nitrogen was the most energy-intensive component (106,590.8 MJ $year^{-1}$), representing nearly half (47.2%) of the total energy for this crop. Direct energy inputs, such as diesel and lubricants used in agricultural operations, accounted for approximately 17.41% of the total.

Similarly, the energy demand for pasture production and maintenance (Table 3) showed a heavy reliance on indirect energy inputs, totalling 77,340.4 MJ $year^{-1}$. Fertilisers were again the primary hotspot, comprising 46.40% of the energy matrix for this subprocess, with nitrogen alone contributing 38.61% of the total. Grass seeds represented a significant share (33.67%), while direct energy inputs (labour and fuel) accounted for 15.28%.

The herd feeding process (Table 4) aggregates the energy embodied in the forage produced on-farm (silage and pasture) with external supplements. This process consumed 483,365.1 MJ $year^{-1}$, representing 87.2% of the farm's total energy input. Corn silage accounted for the largest share (46.73%), followed by commercial concentrate (35.19%) and pasture (16.00%).

In contrast to the agricultural processes, the milking and cooling process (Table 5) was dominated by direct energy sources, chiefly electricity (31,578.0 MJ $year^{-1}$), representing 71.31% of the sector's demand, followed by infrastructure (milking parlour and tank room) at 21.42% and human labour at 7.27% (3,219.3 MJ $year^{-1}$).

The Sanitary Management (Table 6) and Animal Health (Table 7) processes represented smaller fractions of the total energy footprint. Sanitary management was electricity-intensive (83.57%), while the Animal Health sector was driven by indirect energy from veterinary products, particularly other veterinary medications (67.05%) and antibiotics (21.08%).

Global energy performance and consumption profile

The global performance evaluation was based on the commercialised milk volume of 130,263 L (134,170.9 kg). This volume represents the net output sent to the industry, considering that 4,000 L of the total annual production (134,263 L) were retained for calf rearing and on-farm human consumption.

To sustain this commercial production, the system required a total energy input (E_{in}) of 554.6 GJ $year^{-1}$. This value corresponds to the sum of all external inputs (such as fertilisers, diesel, and commercial concentrate) and primary internal resources (labour and infrastructure) effectively consumed by the system. The profile of this energy demand is illustrated in Fig. 3, which identifies herd feeding as the dominant energy sink. This process consumed 483.4 GJ, representing 87.2% of total energy input.

Table 1: Energy coefficients (EC) in accordance with references.

Item	EC	Unit	Reference
Direct energy			
Human labour	1.96	MJ/h	(Dhanapala *et al.*, 2023)
Diesel	35.52	MJ/L	(Ramos *et al.*, 2014)
Lubricants	3.60	MJ/L diesel	(Dalgaard; Halberg; Porter, 2001)
Electricity	5.76	MJ/kWh	(Kamimura *et al.*, 2020)
Indirect energy			
Machinery	12.00	MJ/L diesel	(Dalgaard; Halberg; Porter, 2001)
Installations (cowshed and milking barns)	55.00	MJ/m^2	(Todde *et al.*, 2018b)
Nitrogen	55.30	MJ/kg	(Patiño; Bolívar-Vergara; Rosales, 2025)
Phosphorus (P_2O_5)	15.80	MJ/kg	(Patiño; Bolívar-Vergara; Rosales, 2025)
Potassium (K_2O)	9.30	MJ/kg	(Patiño; Bolívar-Vergara; Rosales, 2025)
Limestone	30.00	MJ/t	(Dalgaard; Halberg; Porter, 2001)
Herbicides	418.20	MJ/L	(Ramos *et al.*, 2014)
Insecticides	363.80	MJ/L	(Ramos *et al.*, 2014)
Fungicides	271.70	MJ/L	(Ramos *et al.*, 2014)
Corn seeds	104.60	MJ/kg	(Müller *et al.*, 2017)
Grass seeds	18.60	MJ/kg	(Müller *et al.*, 2017)
Bionucleus and mineral salt	1.09	MJ/kg	(Ramos *et al.*, 2014)
Commercial concentrate	6.30	MJ/kg	(Patiño; Bolívar-Vergara; Rosales, 2025)
Vaccines	725.20	MJ/L	(Ramos *et al.*, 2014)
Dewormers	45.97	MJ/L	(Ramos *et al.*, 2014)
Antibiotics	522.53	MJ/L	(Ramos *et al.*, 2014)
Other veterinary medications	2518.00	MJ/L	(Ramos *et al.*, 2014)

Table 2: Energy demand for corn silage production.

Input	Quantity (unit yr^{-1})	Energy (MJ yr^{-1})	% of total
Direct energy			
Human labour	105.0 h	205.8	0.09
Diesel	1000.0 L	35520.0	15.72
Lubricants*	1000.0 L	3600.0	1.59
Indirect energy			
Machinery*	1000.0 L	12000.0	5.31
Corn seeds	190.0 kg	19874.0	8.80
Fertilisers			
Nitrogen	1927.5 kg	106590.8	
Phosphorus (P_2O_5)	600.0 kg	9480.0	
Potassium (K_2O)	600.0 kg	5580.0	
Limestone	20.0 t	600.0	
Fert. subtotal		**122250.8**	**54.12**
Pesticides			
Herbicides	40.0 L	16728.0	
Insecticides	32.0 L	11641.6	
Fungicides	15.0 L	4075.5	
Pest. subtotal		**32445.1**	**14.36**
TOTAL USED		**225895.7**	**100.0**

*Based on diesel consumption (Dalgaard; Halberg; Porter, 2001).

Table 3: Energy demand in pasture production.

Input	Quantity (unit yr^{-1})	Energy (MJ yr^{-1})	% of total
Direct energy			
Human labour	40.0 h	78.4	0.10
Diesel	300.0 L	10656.0	13.78
Lubricants*	300.0 L	1080.0	1.40
Indirect energy			
Machinery*	300.0 L	3600.0	4.65
Grass seeds	1400.0 kg	26040.0	33.67
Fertilisers			
Nitrogen	540.0 kg	29862.0	
Phosphorus (P_2O_5)	240.0 kg	3792.0	
Potassium (K_2O)	240.0 kg	2232.0	
Fert. subtotal		**35886.0**	**46.40**
TOTAL USED		**77340.4**	**100.0**

*Based on diesel consumption (Dalgaard; Halberg; Porter, 2001).

Table 4: Energy demand in the feeding process.

Input	Quantity (unit yr^{-1})	Energy (MJ yr^{-1})	% of total
Direct energy			
Human labour	985.5 h	1931.6	0.40
Indirect energy			
Installations	117.5 m^2	6462.5	1.34
Pasture*	-	77340.4	16.00
Corn silage*	-	225895.7	46.73
Commercial concentrate	27.0 t	170100.0	35.19
Mineral salt	1.5 t	1635.0	0.34
TOTAL USED		**483365.1**	**100.0**

*Assuming that all forage and corn silage produced were consumed during the study period.

Table 5: Energy demand in the milking and cooling process.

Input	Quantity (unit yr^{-1})	Energy (MJ yr^{-1})	% of total
Direct energy			
Human labour	1642.5 h	3219.3	7.27
Electricity	5482.3 kWh	31578.0	71.31
Indirect energy			
Installations	172.5 m^2	9487.5	21.42
TOTAL USED		**44284.8**	**100.0**

Table 6: Energy demand in the sanitary management process.

Input	Quantity (unit yr^{-1})	Energy (MJ yr^{-1})	% of total
Direct energy			
Human labour	657.0 h	1287.7	8.86
Electricity	2107.9 kWh	12141.4	83.57
Indirect energy			
Installations	20.0 m^2	1100.0	7.57
TOTAL USED		**14529.1**	**100.0**

Table 7: Energy demand in the animal health process.

Input	Quantity (unit yr^{-1})	Energy (MJ yr^{-1})	% of total
Direct energy			
Human labour	50.7 h	99.3	0.80
Indirect energy			
Installations	10.0 m^2	550.0	4.44
Vaccines	0.5 L	362.6	2.93
Dewormers	10.0 L	459.7	3.71
Antibiotics	5.0 L	2612.7	21.08
Other veterinary medications	3.3 L	8309.4	67.05
TOTAL USED		**12393.7**	**100.0**

In terms of specific inputs (Fig. 4), the profile of the main energy sources reveals that commercial concentrate constitutes the largest component (30.7%), followed by mineral fertilisers excluding limestone (28.4%). Together, these inputs accounted for 59.1% of total energy demand. Diesel (8.3%), seeds (8.3%), and electricity (7.9%) represented the next largest components, followed by pesticides (5.9%). Human labour accounted for only 1.2% of total energy input.

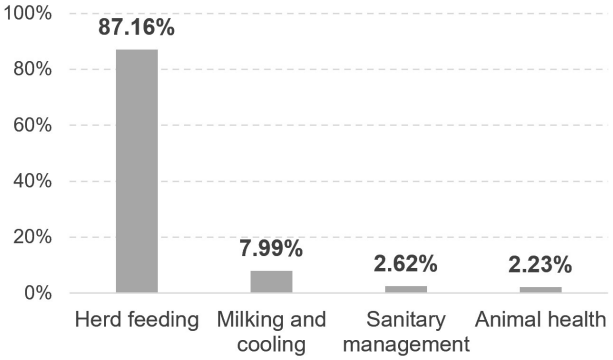


Figure 3: Share of total energy consumption by production process in the family-based dairy system (percentage of total energy demanded).

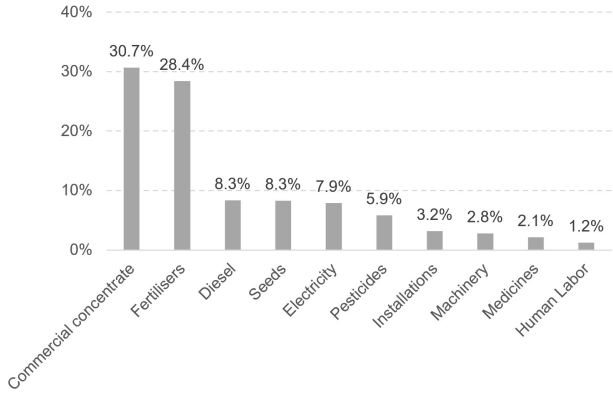


Figure 4: Main components of the system's energy consumption (percentage share).

The global performance indicators are summarised in Table 8. Specific energy consumption was 4.13 MJ kg^{-1} of commercialised milk, and energy productivity was 0.242 kg MJ^{-1}. These indicators were calculated exclusively from the energy inventory and commercial milk output of the investigated system.

Table 8: Energy performance indicators of the family-based mixed dairy system.

Indicator	Value	Unit
Production		
Total annual production	134,263	L year^{-1}
Internal consumption (Calves/Human)	4,000	L year^{-1}
Commercialised milk volume	130,263	L year^{-1}
Commercialised milk mass	134,170.9	kg year^{-1}
Energy input		
Total energy input (E_{in})	554.6	GJ year^{-1}
Performance indicators		
Specific energy consumption (E_{in}/Mass)	4.13	MJ kg^{-1}
Energy productivity (Mass/E_{in})	0.242	kg MJ^{-1}

Energy flow diagram

The energy flow diagram (Fig. 5) maps the trajectory of the 554.6 GJ year^{-1} of total energy inputs demanded by the system. The schematic distinguishes between resources acquired externally and those provided internally, showing their convergence into the specific production processes.

External energy inputs totalled 514.6 GJ. The diagram illustrates the allocation of these resources: inputs associated with forage production (fertilisers, seeds, pesticides, and fuel) are directed towards the pasture management and corn silage production blocks. Electricity is allocated to milking and cooling and sanitary management, veterinary medicines to animal health, and mineral salt and commercial concentrate to herd feeding.

Internal energy inputs (human labour, machinery depreciation, and installations) contributed 40.0 GJ. These flows are distributed across all sectors, supporting the infrastructure required for operation. The diagram identifies herd feeding (483.4 GJ) as the central aggregation point of the system, aggregating the energy requirements of on-farm pasture and corn silage production, commercial concentrate, mineral salt, labour, and installations.

The diagram links the production processes to the commercial milk output of 134.2 t year^{-1}. Energy inputs are expressed in GJ year^{-1}, whereas milk output is expressed in mass units. Dashed arrows indicate productive flows. The diagram also presents the specific energy consumption (4.13 MJ kg^{-1}) and energy productivity (0.242 kg MJ^{-1}).

DISCUSSION

Energy hotspots: commercial concentrate and mineral fertilisation

The energy analysis of this family-based mixed dairy system identified herd feeding as the dominant energy sink (87.2%), a finding consistent with global assessments of livestock systems. A comprehensive review by Paris *et al.* (2022) indicated that feed production typically accounts for over 75% of the total energy consumption in European livestock sectors. Similarly, Shine *et al.* (2020) reported that feed production is responsible for 43% of the total energy on conventional farms, representing the largest single requirement. In the specific context of the current study, both commercial concentrate and agronomic inputs contributed substantially to energy demand.

Commercial concentrate was the largest individual energy input (30.7%). The second major hotspot was mineral fertilisation (N, P_2O_5, and K_2O; excluding limestone), responsible for 28.4% of the farm's total energy footprint. This aligns with findings by Sefeedpari *et al.* (2012), Komleh *et al.* (2011), and Romanelli and Milan (2005) in Brazil, who consistently identified chemical fertilisers as the primary energy bottleneck in maize silage production. Among these nutrients, nitrogen represents the most energy-intensive component (55.3 MJ kg^{-1}), highlighting the energy cost of on-farm forage production even when commercial concentrate is supplemented with locally produced forage.

Specific energy consumption and system typology

The specific energy consumption of 4.13 MJ kg^{-1} and energy productivity of 0.242 kg MJ^{-1} characterise the investigated farm under the adopted inventory boundaries. These indicators provide a quantitative basis for contextualising energy demand across dairy production models and for monitoring changes

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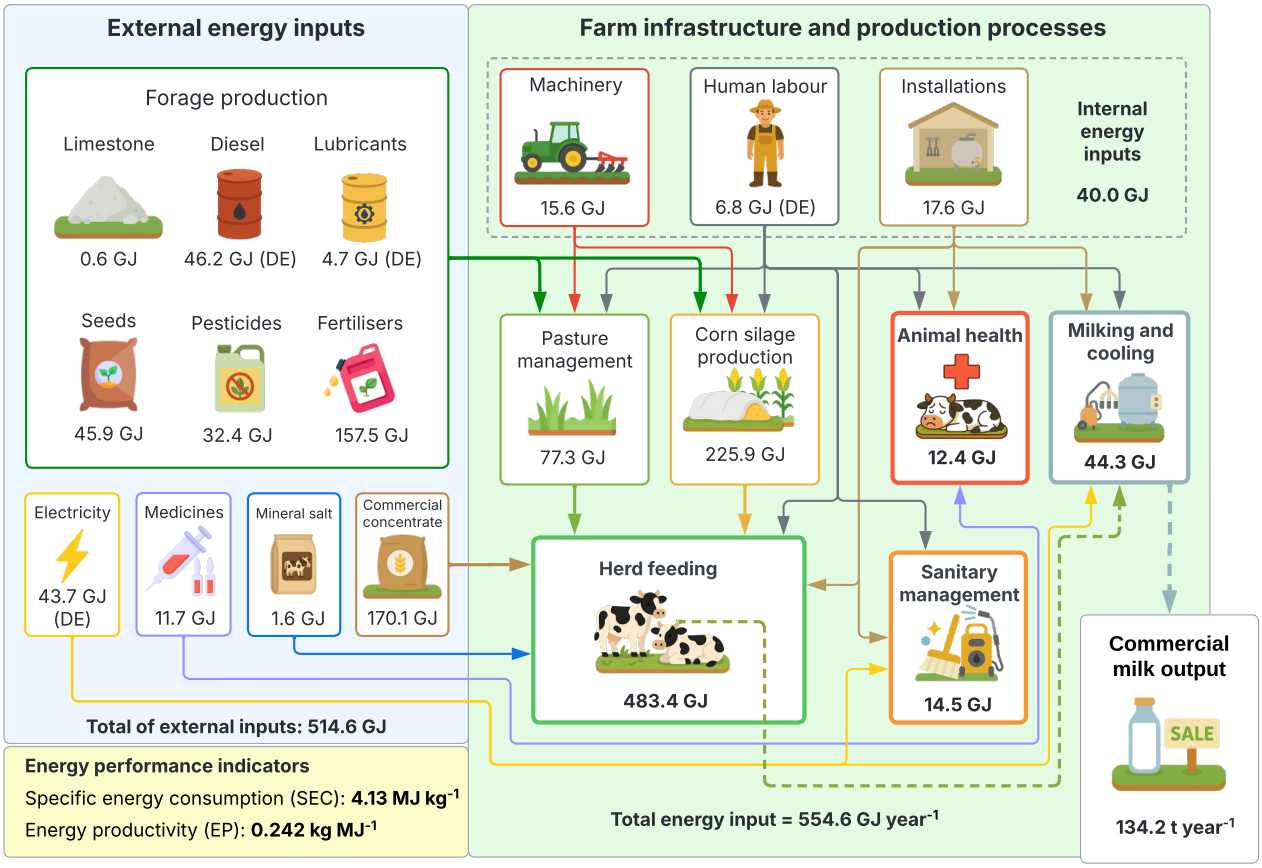


Figure 5: Energy input flows, commercial milk output and energy performance indicators of the family-based mixed dairy system. Energy inputs are expressed in GJ year^{-1} and commercial milk output in t year^{-1}. DE: direct energy. Dashed arrows indicate productive flows. Totals were calculated using unrounded values.

in input use and milk production over time.

In Brazil, Ramos *et al.* (2014) reported a specific energy requirement of 7.42 MJ kg^{-1} for an intensive dairy production system. Herd feeding was an important contributor to energy demand in that system. At the international level, Shine *et al.* (2020) reported mean primary energy requirements of 4.10 MJ kg^{-1} of energy-corrected milk (ECM) for conventional dairy farms, with 4.70 MJ kg^{-1} ECM for confinement systems and 2.80 MJ kg^{-1} ECM for grazing systems. The review by Paris *et al.* (2022) reported a range of 2.10–5.30 MJ kg^{-1} ECM for cow milk production.

The specific energy consumption obtained in the present study was numerically close to the mean reported for conventional dairy farms and between the values reported for conventional grazing and confinement systems. Commercial concentrate and mineral fertilisation both contributed substantially to the accounted energy demand. The medium-intensification typology discussed by Patiño, Bolívar-Vergara, and Rosales (2025) provides context for interpreting these trade-offs between production strategies and resource use.

These comparisons are descriptive rather than a harmonised assessment: the present study uses commercialised milk mass, whereas several international studies use ECM. Differences in functional units, system boundaries, energy coefficients and allocation procedures may influence the reported values. Accordingly, the results characterise the investigated farm without establishing the superiority of one production model over another.

Management practices and resilience

The limited mechanisation in the studied system reflects the labour-intensive nature of family farming in Southern Brazil. As characterised by Balcão *et al.* (2017),

smallholdings in this region often operate with lower mechanisation levels compared to industrial farms. The manual handling of silage and pasture management replaces fossil fuel consumption with metabolic energy (human labour), which, while energetically inexpensive in standard accountings (only 1.2% of total energy input), represents a social constraint. Bernardes and Rêgo (2014) noted that 85% of Brazilian dairy farms still rely on manual silage feed-out, which limits the scale of production but reduces the diesel dependency identified as a major hotspot in European systems by Todde *et al.* (2018a).

From a resilience perspective, the internal use of milk for calf rearing and on-farm silage production may reduce exposure to external input markets (Luiz *et al.*, 2023). These practices may help reduce dependence on purchased inputs and improve resource management.

Strategies for agronomic optimisation and energy autonomy

Given the contribution of commercial concentrate (30.7%) and mineral fertilisation (28.4%), optimisation of feeding and nutrient management represents a priority. Dietary adjustments should be evaluated against animal nutritional requirements and milk production. As highlighted by Komleh *et al.* (2011), the excessive use of chemical fertilisers is a major bottleneck in forage production. In the context of smallholding systems, reducing this dependency requires a shift towards biological nitrogen fixation.

Müller *et al.* (2017), evaluating crop-livestock systems in Southern Brazil, observed that while winter legumes such as vetch (*Vicia sativa*) may have a lower biomass energy yield compared to grasses, they play a crucial role in reducing the demand for non-renewable inputs. Unlike oat-based pastures, which require nitrogen top-dressing, legumes fix atmospheric nitrogen. This agronomic strategy directly addresses one of the principal energy hotspots identified in the present study (mineral fertilisation) offering a pathway to lower the fossil energy footprint of the forage production without requiring heavy capital investments in infrastructure.

Furthermore, while the herd size is modest, the nutrient cycling potential should not be overlooked. The collection of manure from the feeding facilities for use as organic fertiliser can complement the soil management strategy, closing the nutrient loop as suggested by Maciel *et al.* (2022). Finally, taking advantage of the subtropical insolation (25°S), the installation of photovoltaic panels on the existing roof area (320 m^2) offers a viable pathway to mitigate the direct energy costs of milking and cooling, promoting energy autonomy without disrupting the production routine (Paris *et al.*, 2022).

CONCLUSION

The family-based mixed dairy system in Southern Brazil required 554.6 GJ $year^{-1}$ to sustain a commercial milk output of 134,170.9 kg $year^{-1}$. Specific energy consumption was 4.13 MJ kg^{-1} and energy productivity was 0.242 kg MJ^{-1}. These indicators establish a baseline for monitoring energy use in the investigated production system.

Herd feeding accounted for 87.2% of total energy input. Commercial concentrate (30.7%) and mineral fertilisation excluding limestone (28.4%) jointly accounted for 59.1%. These results identify feeding strategies and forage nutrient management as priorities for reducing accounted energy demand.

Evaluation of commercial concentrate use in relation to milk productivity and management strategies such as integrating winter legumes and recycling organic residues may reduce reliance on synthetic nitrogen fertilisers. Renewable electricity generation may also offer opportunities to reduce dependence on purchased energy. The actual effects of these interventions should be evaluated in future studies.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest regarding the publication of this article.

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