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Farm-scale energy analysis of specialized Colombian dairy farms with different levels of intensification

Análise da eficiência energética em fazendas leiteiras da Colômbia com diferentes níveis de intensificação

Luis Miguel Benavides Patiño[1], **Diana María Bolívar-Vergara**[1], **Rolando Barahona Rosales***[1]

1 Universidad Nacional de Colombia, Sede Medellín, Antioquia, Colombia.

*Corresponding author: rbarahonar@unal.edu.co

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Abstract: The use of external inputs, including energy from fossil fuels, and thus their energy use and energy efficiency, are highly variable in specialized dairy farms. Based on input use and productivity, 25 dairy farms were classified as high, medium, or low intensification (eight, eight, and nine, respectively), and their energy use and energy efficiency were quantified. Direct energy use (mJ ha^{-1} $year^{-1}$), mainly electricity use, was higher for the high (10,778) and medium (7,990) intensification farms than for the low-intensification farms (4,645; $P < 0.05$). Indirect energy use (% of total energy usage) was mainly due to supplementation (45%, 41%, and 36%) and fertilization (43%, 40%, and 46%) for the high-, medium-, and low-intensification farms, respectively. The energy output (i.e., the energy in meat and/or milk) was mainly concentrated in milk (97.1%, 96.0, and 96.7% of total energy production for the high-, medium-, and low-intensification farms, respectively). The medium-intensification farms had the highest energy efficiency (output/input = 0.72) compared with the high- and low-intensification farms (0.55 and 0.59, respectively, $P < 0.05$). Likewise, at each level of intensification, as the use of inputs increased, energy efficiency tended to be lower ($P < 0.05$). To increase energy capture in livestock products, it is necessary to guarantee adequate technical management of production systems and a balanced use of inputs.

Keywords: Energy efficiency; livestock; intensification of production systems.

Resumo: O uso de insumos (*input*), incluindo energia proveniente de combustíveis fósseis, e, consequentemente, o consumo energético e a eficiência energética, são altamente variáveis em fazendas leiteiras especializadas. Com base no uso de insumos e na produtividade, 25 fazendas leiteiras foram classificadas em três níveis de intensificação: alta, média e baixa (oito, oito e nove propriedades, respectivamente), e seus consumos e eficiências energéticas foram quantificados. O consumo direto de energia ($mJ\ ha^{-1}\ ano^{-1}$), predominantemente devido ao uso de eletricidade, foi maior nas fazendas de alta (10.778) e média (7.990) intensificação em comparação com as de baixa intensificação (4.645; $P < 0,05$). O consumo indireto de energia (% do consumo total) esteve principalmente associado à suplementação alimentar (45%, 41% e 36%) e à adubação (43%, 40% e 46%) nas fazendas de alta, média e baixa intensificação, respectivamente. A saída de energia (*output*), ou seja, a energia contida no leite e/ou na carne, foi majoritariamente atribuída à produção de leite (97,1%, 96,0% e 96,7% da produção total de energia para as fazendas de alta, média e baixa intensificação, respectivamente). As fazendas de média intensificação apresentaram a maior eficiência energética (relação saída/entrada = 0,72) em comparação com as fazendas de alta e baixa intensificação (0,55 e 0,59, respectivamente, P < 0,05). Além disso, em todos os níveis de intensificação, à medida que o uso de insumos aumentava, a eficiência energética tendia a ser menor (P < 0,05). Para aumentar a retenção de energia nos produtos de origem animal, é fundamental garantir um manejo técnico adequado dos sistemas produtivos e um uso equilibrado dos insumos.

Palavras-chave: Eficiência energética; pecuária; intensificação de sistemas produtivos.

1. Introduction

For many years, global energy demand has been satisfied by using fossil fuels, which have accounted for 81.8% of the global energy demand, mainly through the use of coal, natural gas, and oil. On the other hand, renewable energy meets only 7.5% of this demand (1). One of the concerns associated with our use of fossil fuels is related to climate change due to the increase in the atmospheric concentration of greenhouse gases (GHGs), the emissions of which are directly related to our consumption of fossil fuels (2).

Although animal agriculture is not one of the world's most fossil-fuel-energy-intensive economic sectors, intensifying livestock systems may lead to greater reliance on using fertilizers, agrochemicals, and fuels, products that consume fossil fuel energy for their production (3). This fossil fuel energy consumption contributes directly and indirectly to GHG emissions, which include carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) (4), and reduces the system's profitability by increasing production costs (5). Therefore, analyzing energy use is very important in assessing the sustainability of agricultural systems (6). This evaluation allows to determine the differences in efficiency and productivity and to achieve greater precision in the management of the system by focusing the corrections in the areas of lower efficiency and productivity.

In general, the dynamics and efficiency of using natural resources are unknown in the tropics, including livestock systems for milk production. Thus, little is known about the energy, environmental, and economic sustainability of these systems, although it is recognized that the use and efficiency of energy are quite variable because depend on the productive intensification of the production model and external inputs. Our hypothesis is that highly-intensified farms dedicated to milk production have higher efficiency and utilization of energy.

Although many producers are aware of the environmental impact generated by their productive activity, they lack the necessary information to improve system efficiency and to optimize the use of inputs, production parameters, and product quality. To bridge this knowledge gap, the present study evaluated the energy use (fossil fuels, electricity, and energy from the feed supplied to animals and in the products obtained) in specialized dairy farms in northern Antioquia with different levels of intensification.

2. Material and methods

2.1 Location

The study was carried out in northern Antioquia, a region characterized by its specialized dairy cattle activity and as one of the main dairy basins of Colombia. out of 60 farms, 23 with the necessary data for this research were selected. These farms were in the municipalities of Bello (n = 3), Belmira (n = 6), Don Matías (n = 1), Entrerríos (n = 1), San José de la Montaña (n = 6), San Pedro de los Milagros (n = 3), and Yarumal (n = 3). These farms have average temperatures ranging from 13.5 to 16°C, altitudes between 2200 and 2700 m above sea level, and are predominantly located in low mountain humid forest (bh-MB) and very humid mountain forest (bmh-M).

2.2 Technical aspects of production systems

The livestock systems studied share several general characteristics in their production model. For example, the grass used on the farms is kikuyu grass (*Cenchrus clandestinus* Hoechst Ex Chiov.), with rotational grazing with an electric fence and two daily grazing strips - one in the morning and afternoon. Paddock rotation times ranged from 35 to 45 days, and cattle belong to the Holstein breed. However, the farmers use various milking systems, including mechanical milking in a parlor, mechanical milking in a pasture, and manual milking in a pasture.

The farms were grouped according to their level of intensification based on three parameters: (a) litters of milk per hectare sold annually (L ha^{-1} $yr.^{-1)}$, (b) the use of nutritional supplementation (kg ha^{-1} $yr.^{-1}$), and (c) the use of fertilizer (kg ha^{-1} $yr.^{1}$). For high-intensification farms, ≥ 12,000 L ha^{-1} $yr.^{-1}$ milk is sold, nutritional supplementation is ≥ 5,000 kg ha^{-1} $yr.^{-1}$, and fertilizer use is ≥ 1,500 kg ha^{-1} $yr.^{-1}$. On medium-intensification farms, between 7,501 and 11,999 L ha^{-1} $yr.^{-1}$ milk is sold, nutritional supplementation is between 2,001 and 4,999Kg ha^{-1} $year^{-1}$, and fertilizer use is between 701 and 1,499 kg ha^{-1} $yr.^{-1}$. Finally, on low-intensification farms, ≤ 7,500 L ha^{-1} $yr.^{-1}$ milk is sold, feed supplementation is ≤ 2000 kg ha^{-1} $yr.^{-1}$, and fertilizer use is ≤ 700 kg ha^{-1} $yr.^{-1}$.

2.3 Energy analysis

The methodology implemented for the energy analysis was based on flow and energy accounting model accounting for three components: direct and indirect energy inputs, energy outputs in the form of products, and conversion factors [3, 7, 8].

2.4 Energy inputs

Two forms of energy input were considered: direct and indirect (Table 1). Direct energy input includes electricity, diesel, gasoline, and liquefied petroleum gas. Indirect energy input includes animal supplementation and pasture management. Animal supplementation comprises all indirect energy costs related to commercial concentrates, by-products (orange peel, potato, or other), feeds (cracked corn, extruded corn, cottonseed, soybean meal, etc.), nutritional blocks, mineralized salts, molasses, corn silage, and other products used as animal feed. Pasture management consists of all indirect energy costs related to fertilization and the control of weeds, pests, and insects. This includes the use of soil amendments, chemical fertilizers, organic fertilizers, foliar fertilizers, herbicides, insecticides, fungicides, and others. Fertilizers, herbicides, and insecticides were applied manually. Finally, total energy input was calculated as the sum of direct and indirect inputs.

2.5 Factors not considered

Three energy inputs were not considered: labor, veterinary medicine, and machinery. Although human labor costs can be included in the energy analysis, they were not considered here because rural employment provides significant social benefits. Including farm workers' energy expenditure would create a negative correlation between workforce size and farm energy efficiency, which is unfair given the social importance of rural employment. Although various veterinary medicines are used in productive systems, the low usage volume (compared with other inputs) and the lack of records on their use or disposal made them irrelevant for this analysis. For the same reason, many energy analyses in the literature also exclude this input. Finally, primary machinery used on these farms consists of milking machines and, to a limited extent, tractors. The concept of "embedded energy" for this machinery was not included. However, gasoline and electricity required for its operation were included.

Table 1. Parameters and indicators used in this study.

Parameters	**Composition**
Direct energy input (dEI)	Diesel + electricity + lubricants + others
Indirect energy input (iEI)	Fertilizers+concentrates+forages+herbicides+others
Energy input (EI)	EI = dEI + iEI
Energy output (EO)	Energy in the products
Indicators	Definition
Energy efficiency (EE)	EE = EO/EI
Energy productivity (EP)	EP = Product obtained/EI

2.6 Energy output

The energy output of the system was calculated based on the milk and meat produced. The energy exported through milk was calculated using the equation proposed by the NRC [9]:

Milk energy (mJ kg^{-1}) = (0.0929 × % Fat + 0.0588 × % Protein + 0192) × 4.184.

2.7 Milk quality determinations

Milk quality from the 25 livestock farms was measured in the Milk Control Program of the Investigación Láctea para Antioquia – ILA Project conducted by the University of Antioquia and the National University of Colombia, Medellín campus. Milk quality assessment was performed every 6 weeks on samples from the afternoon (PM) milking. Individual milk samples from all animals and from total milk accumulated in the cooling tanks were analyzed at the Laboratory of Quality and Safety of Milk of the Faculty of Agrarian Sciences of the University of Antioquia. The analyses were performed using BactoScan™ FC+ and CombiFoss™ FT+ equipment. Fat, protein, total milk solids, and milk urea nitrogen (MUN) were measured.

2.8 Estimated indicators

Energy efficiency was defined as the ratio of energy produced (energy output) to total energy input [3, 10]. Energy productivity is the ratio of the quantity of product obtained to the energy required for its production [3, 10]. The functional units adopted to evaluate the system productivity were litters of milk, kilograms of milk fat, kilograms of milk protein , and kilograms of milk total solids sold.

2.9 Factors of energy equivalence

The amount of each input used by the system was multiplied by its energy equivalence factor (Table 2), to quantify the net energy input and calculate the energy balance.

2.10 Statistical analysis

The data were analyzed using the GLM procedure in the SAS software following a completely randomized design. Mean values were compared to Duncan's test with an alpha of 0.05. Additionally, linear regression analyses were performed to determine relationships between the variables.

Table 2. Factors of energy equivalency (FEE) used to account for energy input.

Element	Unity	FEE	References
Direct			
Diesel	mJ/L	40.6	(11, 12)
Lubricants	mJ/L	3.6	(11)
Electricity	mJ/kW	14.4	(13)
Gasoline	mJ/L	46.3	(14)
Indirect[1]			
Nitrogen	mJ/kg	55.3	(11, 12, 15, 16)
Phosphorus	mJ/kg	15.8	(12)
Potassium	mJ/kg	9.3	(12)
Concentrates	mJ/kg	6.3	(17)
Corn	mJ/kg DM	14.5	(18)
Guandul	mJ/kg	14.1	(19)
Soy	mJ/kg	18.1	(19)
Orange peel silage	mJ/kg	1.9	(14, 20)
Cottonseed	mJ/kg	11.8	(21)
Corn silage	mJ/kg DM	12.9	(18)
Soybean seed	mJ/kg	25.0	(20)
Rice	mJ/kg	14.7	(18)
Wheat	mJ/kg	15.7	(19)
Grass	mJ/kg DM	12.8	(18)
Oats	mJ/kg DM	16.3	(13)
Herbicides	mJ/kg DM	214.0	(11, 12, 15)
Insecticides	mJ/kg	278.0	(11, 12)
Fungicides	mJ/kg	276.0	(11, 12)
Machinery	mJ/L diesel	12.0	(11)

[1] *The energy equivalence values were not associated with the energy cost to produce them, but rather with their energy contents.*

3. Results and discussion

3.1 Technical and productive characterization of the systems

The characteristics of the farms, grouped by their intensification level, are shown in Table 3. High-intensification farms had a production area of 26.8 ± 17.4 ha and 70 ± 49 cows in milk. Medium-intensification farms had a production area of 25.7 ± 18.9 ha and 38 ± 22 cows in milk. Finally, the low-intensification farms had a production area of 37.1 ± 21.0 ha and 37 ± 28 cows in milk.

Table 3. Technical and productive characteristics of the evaluated dairy farms.

Item	Low	Medium	High	P value
Farms, number	9	8	8	
Area, ha				
Forest area	0.71 ± 1.53	6.03 ± 9.19	2.66 ± 5.59	
Production area	37.1 ± 21.0	25.7 ± 18.9	26.8 ± 17.4	
Total area	37.8 ± 21.9	31.8 ± 26.4	29.4 ± 22.3	
Direct energy expenditure				
Electricity, kWh ha^{-1} $year^{-1}$	364 ± 527	565 ± 928	741 ± 863	
Gasoline, L ha^{-1} yea^{r-1}	7.27 ^{b}	23.15 ^{a}	17.02 ^{a}	<0.05
Supplementation, kg ha^{-1} $year^{-1}$				
Concentrates	1,602 ^{c}	2,760 ^{b}	5,041 ^{a}	<0.05
Other supplements	56 ^{b}	151 ^{b}	2,107 ^{a}	<0.05
Salt	57	95	163	<0.05
Total supplementation	1,719 ^{b}	2,984 ^{b}	7,301 ^{a}	<0.05
Pasture management				
Nitrogen, kg ha^{-1} $year^{-1}$	206 ^{c}	316 ^{b}	632^{a}	<0.05
Phosphorus, kg ha^{-1} $year^{-1}$	62 ^{b}	42 ^{b}	217^{a}	<0.05
Potassium, kg ha^{-1} $year^{-1}$	39 ^{b}	42 ^{b}	137^{a}	<0.05
Total fertilization, kg ha^{-1} $year^{-1}$	667 ^{b}	940 ^{b}	2,088 ^{a}	<0.05
Herbicides and insecticides, L ha^{-1} $year^{-1}$	2.48 ^{b}	2.75 ^{b}	8.55 ^{a}	<0.05
Production				
Cows in milk, number	37 ± 28	38 ± 22	70 ± 49	
Cows in milk, number ha^{-1}	1.03 ± 0.29	1.74 ± 0.47	2.54 ± 0.35	
Milk exported, l day^{-1}	576 ± 463	696 ± 485	1,227 ± 709	
Total exported milk, L ha^{-1} $year^{-1}$	5479 ^{c}	10724 ^{b}	17285 ^{a}	<0.05
Milk fat, %	3.79	3.78	3.62	
Milk fat, kg ha^{-1} $year^{-1}$	207 ^{c}	403 ^{b}	621^{a}	<0.05
Milk protein, %	3.15	3.15	3.11	
Milk protein, kg ha^{-1} $year^{-1}$	173 ^{c}	337 ^{b}	536^{a}	<0.05
Total solids, %	12.28	12.24	12.15	
Total solids, kg ha^{-1} $year^{-1}$	672 ^{c}	1,310 ^{b}	2,100 ^{a}	<0.05
MUN, mg dl^{-1}	18.65	18.71	17.87	

a, b, c Means in the same row with different superscript letters are significantly different (P < 0.05). Low, medium, and high refer to different levels of farm intensification.

Regarding saleable milk, high- and medium-intensification farms produced 3.15 and 1.96 times more milk (ha^{-1} $yr.^{-1}$) than the low-intensification farms. Likewise, milk fat production (kg ha^{-1} $yr.^{-1}$) was 3.01 and 1.95 times higher in the high- and medium-intensification farms than the low-intensification farms (P < 0.05). Moreover, milk protein and total solid production (kg ha^{-1} $yr.^{-1}$) were higher for the high-intensification (3.09 and 3.13 times, respectively) and medium-intensification (1.95 and 1.95 times, respectively) farms than the low-intensification farms (P < 0.05; Table 3).

Total fertilizer use was highest in high-intensification farms, being 2.2 times higher than in the medium-intensification farms and 3.13 times higher than in low-intensification farms. Nitrogen fertilizers, primarily used for pasture fertilization, represented the main input in all cases (Table 3) and accounted for 30%, 34%, and 31% of all fertilizers used in high-, medium-, and low-intensification farms, respectively.

Regarding to direct energy use, fuel consumption was higher in high- and medium-intensification farms (17.02 and 23.15 L ha^{-1} $yr.^{-1}$, respectively) than for the low-intensification farms (7.27 L ha^{-1} yr^{-1}). Electricity use (kWh ha^{-1} $yr.^{-1}$) represented the highest input of direct energy (Table 3).

3.2. Energy analysis of the production systems

The quantification of energy input, both direct and indirect, as well as energy output, is shown in Table 4. Direct energy used was mainly associated with electricity consumption, accounting for 11.3%, 17.0%, and 15.8% of total energy input for the high-, medium-, and low-intensification farms, respectively. High- and medium-intensification farms used significantly more energy compared with the low-intensification farms (P < 0.05; Table 4).

Table 4. Energy input and output (mJ ha^{-1} $year^{-1}$) on dairy farms with different levels of intensification.

Item	Low	Medium	High	P value
Direct energy input (dEI)				
Electricity	4,645 ^{b}	7,990 ^{ab}	10,778 ^{a}	<0.05
Gasoline	786	887	649	
Total dEI	5,430 ^{b}	8,878 ^{ab}	11,427 ^{a}	<0.05
Indirect energy input (iEI)				
Supplementation				
Concentrates	10,094 ^{c}	17,391 ^{b}	31,760 ^{a}	<0.05
Supplements	260 ^{b}	1,291 ^{ab}	10,001 ^{a}	<0.05
Salts	77 ^{b}	120 ^{b}	201 ^{a}	<0.05
Total supplementation	10,431 ^{b}	18,801 ^{b}	41,961 ^{a}	<0.05
Pasture management				
Nitrogen	11,415 ^{b}	17,474 ^{b}	34,947 ^{a}	<0.05
Phosphorus	987 ^{b}	663 ^{b}	3,429 ^{a}	<0.05
Potassium	361 ^{b}	391 ^{b}	1,270 ^{a}	<0.05
Herbicides and insecticides	688 ^{b}	762 ^{b}	2,369 ^{a}	<0.05
Total pasture management	13,451 ^{b}	19,290 ^{b}	42,014 ^{a}	<0.05
Total iEI	23,882 ^{c}	38,091 ^{b}	83,976 ^{a}	<0.05
Total energy input (dEI + iEI)	29,312 ^{c}	46,969 ^{b}	95,403 ^{a}	<0.05
Energy output (EO)				
Sold milk	16,672 ^{c}	32,534 ^{b}	51,133 ^{a}	<0.05
Sold meat	576 ^{c}	1,248 ^{b}	1,554 ^{a}	<0.05
Total EO	17,248 ^{c}	33,782 ^{b}	52,687 ^{a}	<0.05
Balance	12,064 ^{c}	13,187 ^{b}	42,716 ^{a}	<0.05

a, b, c Means in the same row with different superscript letters are significantly different (P < 0.05). Low, medium, and high refer to different levels of farm intensification.

Indirect energy use was mainly associated with supplementation and fertilization. Supplementation accounted for 44%, 40%, and 36% of total energy input in high-, medium-, and low-intensification farms, respectively. Among the supplementation procedures, concentrates were the main indirect energy input, with variations across farm intensification levels (Table 4). Additionally, high-intensification farms had a higher indirect energy input from other supplements than medium- and low-intensification farms (Table 4).

Fertilization contributed 44%, 41%, and 46% of total indirect energy input in high-, medium-, and low-intensification farms, respectively. The energy input from supplementation and fertilization (mJ ha^{-1} yr^{-1}) was significantly higher for high-intensification farms compared to medium- and low-intensification farms ($P < 0.05$). All farms showed a high dependence on nitrogen-based fertilization, but high-intensification farms had the highest energy input from nitrogen fertilizers. In addition, the total energy cost of fertilization was higher for the high-intensification farms than in medium- and low-intensification farms ($P < 0.05$; Table 4).

Indirect energy input (supplementation and fertilization) accounted for the majority of total energy input in the evaluated dairy farms, representing the 88%, 81%, and 82% of total energy in high-, medium-, and low-intensification farms, respectively. For all farms the most energetic inputs were nitrogen fertilizers, concentrates, and electricity. However, the relative contribution of each input (as percentage of total energy input) varied among the intensification levels. The highest energy expenditure in these systems was associated eith animal feeding, either directly (through concentrates and supplements) or indirectly (through pasture management).

Energy output from milk production accounted for 97.1%, 96.0%, and 96.7% of total energy output in high-, medium-, and low-intensification farms, respectively. High-intensification farms had the highest energy output (mJ ha^{-1} yr^{-1}) and milk production, while the low-intensification farms had the lowest energy output (Table 4).

3.3 Energy indicators

The energy balance, shown in Table 5, suggested energy inefficiency across all farms, as more energy was consumed than exported as a product. The high-intensification farms had the highest balance (input minus output) - 3.24 and 3.54 times more than the balance of the medium- low-intensification farms, respectively. The energy efficiency of medium-intensification farms was the highest - 0.72 compared to 0.55 and 0.59 for high- and low-intensification farms, respectively (Table 5).

Table 5. Energy indicators on dairy farms with different levels of intensification.

Item	Low	Medium	High	P value
Energy efficiency	0.59^{b}	0.72^{a}	0.55^{b}	<0.05
Energy productivity, L milk 100 mJ^{-1}	$19,15^{b}$	23.05^{a}	18.05^{b}	<0.05
Energy productivity, kg milkfat 100 mJ^{-1}	$0,73^{ab}$	0.87^{a}	0.65^{b}	<0.05
Energy productivity, kg milk protein 100 mJ^{-1}	0.60^{b}	0.73^{a}	0.56^{b}	<0.05
Energy productivity, kg milk total solids 100 mJ^{-1}	2.35^{ab}	2.82^{a}	2.19^{b}	<0.05

a, b, c Means in the same row with different superscript letters are significantly different (P < 0.05). Low, medium, and high refer to different levels of farm intensification.

3.4 Use of inputs

There were differences among farms in the import of concentrates, other supplements, and total supplements (Table 3). Concentrates were the main energy input among the nutritional supplements used in all the studied systems. In particular, in high-intensification farms, producers more frequently implemented feeding strategies different from commercial concentrates, such as corn silage, orange peel silage, soybean meal, and cottonseed, among others, which are usually more accessible or cost-effective.

For the evaluated farms - and dairy farms in Colombia in general - it is common to apply nitrogen fertilizers, particularly urea, after each grazing [(22)] due to the increase in forage biomass available in response to fertilization. This favourable outcome is easily noticeable to producers as it leads to higher stocking rates and increased milk production per hectare. Furthermore, fertilization enables grazing on younger and higher quality pastures [(23, 24)].

Nitrogen fertilization accounted for more than 30% of all fertilizer used (Table 3). Notably, while the medium-intensification farms used 0.28 kg of nutritional supplements per litter of milk, high-intensification farms used 0.42. On the other hand, fertilizer use per litter of milk was 0.087 in medium- intensification farms and 0.120 kg in high-intensification farms. This demonstrates that conventional intensive farming systems rely heavily on fossil fuel energy and industrially synthesized products [(25)].

The indirect energy from fertilization and concentrates in this study is similar to what Cederberg and Mattsson [(26)] reported, i.e., supplementation and fertilization accounted for at least 36% and 40%, respectively, of total energy input. On the other hand, direct energy is primarily associated with farm technification, as it is mainly used by milking machines and cooling systems. Notably, this equipment is not necessarily present in all farms. For instance, farms at all levels of technification may use mechanical milking systems in a parlor or directly on a pasture, or they employ manual milking. Similarly, some farms may lack of cooling tanks, or use a community-owned cooling tank instead. Overall, the increase of energy input as a function of farm intensification reported in this study is consistent with what was reported by Llanos et al. [(27)] for milk systems in Uruguay, where energy input increased as farm productivity increased.

3.5 Energy efficiency

The energy efficiency indicator represents the ratio of energy produced (energy output) to energy input [(3,10)]. If this indicator equals 1, the evaluated systems are considered energetically sustainable, as their energy output equals their expenditures. Systems with an energy efficiency higher than 1 are classified as energy efficient, meaning that they produce more energy than they consume. Conversely, systems with an energy efficiency lower than 1 are considered inefficient as they demand more energy than the energy they produce. Livestock systems can be energy efficient: In one study, the energy efficiency was 2.31 [(28)].

The energy efficiency of medium-intensification farms was higher than in high- and low-intensification farms (Table 5), suggesting that a balanced approach to the use of supplements and fertilizers is necessary to achieve adequate energy efficiency in dairy farms. Although grass-and-legume-based feed systems consume less energy than those based on concentrates [29], they may also be associated with lower animal productivity, which could reduce overall energy efficiency. In the present study, the evaluated farms showed high dependence on nitrogen fertilization. While this practice increases forage availability, it should be complemented by effective grazing management to optimize forage intake by grazing animals. This explains the significant variability reported for livestock systems. For example, in Argentina, Denoia et al. [30] estimated an efficiency of 0.2 for milk production systems and mixed production systems (milk and meat). In contrast, in Uruguay Llanos et al. [27] found that livestock systems with low milk productivity had an efficiency of 1.4, while systems with high and medium productivity had an efficiency of 0.86 and 0.90, respectively.

Moreover, biological systems have an upper limit in their ability to respond to various stimuli. Excessive inputs can overwhelm the system reducing the ability of animals to efficiently harvest and utilize available feeds. The higher efficiency observed in medium-intensification farms may be attributed to their balanced use of inputs (supplements and fertilizers). In contrast, low-intensification farms may experience limited production capacity due to insufficient supplementation and fertilization, resulting in lower energy efficiency. Contrary, in high-intensification farms, high inputs allow higher forage production. However, the lower energy efficiency observed in this study is likely due to the underutilization of the available forage (undergrazing) - partly due to grazing management and partly due to greater concentrate feeding. A balanced supply of forage is crucial to ensure both adequate diet intake by the animals [31, 32, 33] and adequate productivity of the system [34].

In medium-intensification farms, the fertilization rate was 316 kg-Nha^{-1}yr^{-1}, which may indicate a higher rate of utilization of nutrients by plants, compared to high-intensification farms, where the fertilization rate was 632 kg-Nha^{-1}yr^{-1}, suggesting a higher likelihood of nitrogen losses. Meanwhile, in low-intensification farms, the fertilization rate was 206.4 kg-Nha^{-1} yr $^{-1}$, which may limit forage availability.

There was a direct relationship between the energy input and output at all levels of intensification (See Figure 1). High-intensification farms had the steepest slope ($y = 0.5876x + 3402.5$; $R^2 = 0.5725$), followed by the medium-intensification farms ($y = 0.5684x + 7085.2$; $R^2 = 0.7545$) and the low-intensification farms ($y = 0.4072x + 5311$; $R^2 = 0.5993$).

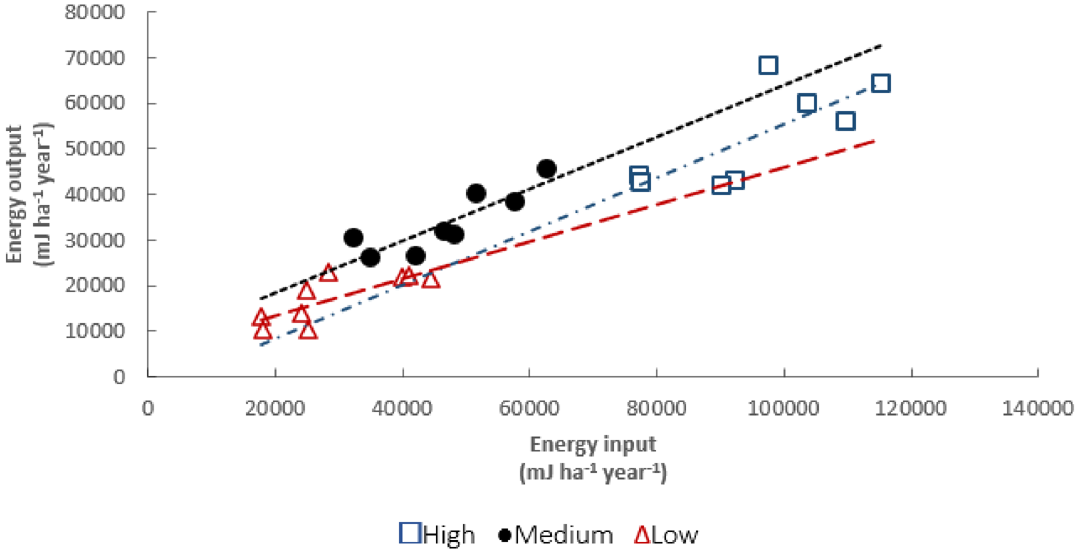

Figure 1. Relationship between the energy input and output of dairy farms with different levels of intensification.

The linear regression analysis between fertilization and energy efficiency (Figure 2) suggests that energy efficiency tends to improve at intermediate levels. The inverse relationship between energy efficiency and fertilizers (Figure 2) highlights the need for careful fertilizer management to enhance the energy efficiency of these systems. The low- and high-intensification farms showed a more pronounced inverse relationship between energy efficiency and fertilizers. However, further analysis is needed to assess how fertilizer levels influence supplementation, animal breeding, and livestock herd management practices and draw more accurate conclusions. This is particularly important because some farms with very different levels of fertilization exhibited similar energy efficiency.

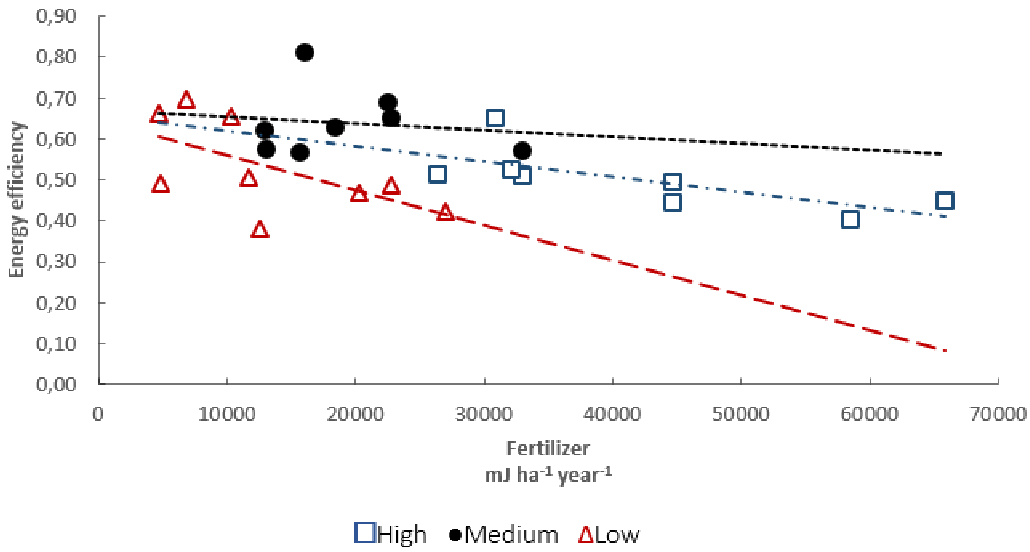

Figure 2. Relationship between energy efficiency and energy input due to fertilization for dairy farms with different levels of intensification.

Energy productivity was highest for the medium-intensification farms, which produced 23.05 L of milk, 0.87 kg of milk fat, 0.73 kg of milk protein, and 2.82 kg of milk total solids per 100 mJ of energy used (Table 5). In France, Le Gall et al. [29] reported higher energy productivity for dairy farms with feeding systems based on legumes (30.03 L / 100 mJ^{-1}) and grasslands

(29.07 L / 100 mJ^{-1}), and lower productivity for mixed systems (26.31 L 100 mJ^{-1}) and those based on the use of concentrates (26.6 L 100 mJ^{-1}).

Denoia et al. [30] reported energy productivity similar to that estimated in the present study, namely 17.85 L 100 mJ^{-1} for milk and meat production systems and 13.3 L 100 mJ^{-1} for milk-only systems. In Uruguay, researchers reported an energy productivity of 49.02, 31.05, and 21.3 L 100 mJ^{-1} for low-, medium-, and high-intensity farms, respectively. This suggests that energy productivity can be improved in most livestock systems.

It is noteworthy that the use of agricultural inputs in dairy farms contributes to their GHG emissions. Of particular interest in this study are N2O emissions associated with fertilization practices and crop residues, CO2 emissions associated with the production of nutritional supplements, and GHG emissions derived from direct and indirect energy use [35]. In response to the current environmental problems on the planet, methodologies to calculate the environmental impact of different forms of production have significantly advanced in recent years. However, none of these indicators has provided a universal understanding of how human activity affects the planet. Energy analysis [36, 37] can help to establish the relationship between the use of different energy sources, such as fossil fuels, electricity, and the food supplied to animals to their environmental impacts. Assessing the energy efficiency of a production system enhances understanding of the system's performance and energy use and can help to implement a more efficient production system with a lower environmental impact. Therefore, it is advisable to include energy analysis when evaluating farm parameters such as the contribution to food security and job creation, among others.

4. Conclusion

Medium-intensification dairy farms were the most energy-efficient system and showed the best production parameters, requiring less energy to produce milk and its components. The decrease in energy efficiency observed in high-intensification farms was associated with high fossil fuel energy consumption, due to high use of concentrates for animal supplementation and high fertilization products. Since fossil fuel energy use is linked to greater negative environmental impact, reducing dependence on non-renewable energy is essential. This can be achieved by measuring farm productivity alongside farm energy efficiency.

Supplementary material

Graphical Abstract (only available in the electronic version).

Conflicts of interest statement

The authors declare that there is no conflict of interest.

Data availability statement

The data will be provided upon request.

Author contributions

Conceptualization: D. M. Bolívar-Vergara and R. Barahona Rosales. Data curation: L. M. Benavides Patiño. Formal analysis: D. M. Bolívar-Vergara. Funding acquisition: D. M. Bolívar-Vergara and R. Barahona Rosales. Project management: D. M. Bolívar-Vergara. Methodology: R. Barahona Rosales. Supervision: D. M. Bolívar-Vergara and R. Barahona Rosales. Investigation: L. M. Benavides Patiño. Visualization: L. M. Benavides Patiño. D. M. BolívarVergara and R. Barahona Rosales. Writing (original draft): L. M. Benavides Patiño. Writing (proofreading and editing): D. M. Bolívar-Vergara and R. Barahona Rosales.

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