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Silvopastoral systems with native forage species and their impact on milk production and quality: a case study on a farm in the Colombian Amazonian foothills

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Abstract This study compared a silvopastoral system (SPS) with promising shrub and tree species against a traditional grazing system (TS) in the Amazonian foothills of Colombia, evaluating milk production and composition, dry matter intake (DMI), and economic performance. A crossover design was applied with 10 lactating gyr × holstein crossbreed cows. Dry matter intake, milk production and feed efficiency were significantly greater ($p<0.001$) in the SPS (12.90 kg DM/day, 14.13 kg/cow/day, and 1.24 milk kg/kg DM) compared to TS (10.5 kg DM/day, 12.92 kg/cow/day, and 1.17 kg milk kg/kg DM) respectively. Although milk composition did not differ ($p>0.05$) between systems, milk urea nitrogen (MUN) was greater in the SPS (11.9 vs. 10.2 mg/dL; $p<0.001$), which reflects a greater protein intake consistent with the forage composition provided by this system. The SPS required a greater initial investment (USD 2240.85 vs. USD 501.62), resulting in a 4.08% increase in the production cost per kilogram of milk (USD 0.37 vs. USD 0.36). Nevertheless, the SPS demonstrated greater profitability, with a benefit-to-cost ratio (B/C) of 2.05, a greater net present value, and a shorter payback period (3.5 years). These results, highlight the potential of SPS as an effective strategy for improving dairy productivity and feed efficiency while mitigating environmental pressures in tropical livestock systems.

Keywords Agroforestry · Forage intake · Dairy productivity · Ruminant nutrition · Tropical agroecosystems

Abbreviations

SPS	Silvopastoral system
TS	Traditional grazing system
DMI	Dry matter intake
DM	Dry matter
CP	Crude protein
NDF	Neutral detergent fiber
ADF	Acid detergent fiber
NEL	Net energy for lactation

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MUN Milk urea nitrogen
GHG Greenhouse gas
FPCM Fat- and protein-corrected milk
BCS Body condition score
NC Number of calvings
DIM Days in milk

Introduction

Livestock farming in tropical regions is challenged by extensive and often inefficient management of natural resources, including soil degradation, biodiversity loss, and a significant increase in greenhouse gas (GHG) emissions (Pezo 2017; Zapata-Cadavid and Silva-Tapasco 2020). Additionally, tropical forages, which are generally characterized by low yields and poor nutritional quality, are affected by climatic variability, reflected in their low crude protein and soluble carbohydrate content, high fiber concentration, and low digestibility, directly impacting ruminant productive performance (López-Vigoa et al. 2017). These issues are particularly severe in the Amazonian foothills, a strategic and sensitive ecosystem that, despite its rich biodiversity, is highly vulnerable to the adverse effects of conventional livestock practices (Clavijo-Ponce 2024).

Silvopastoral systems (SPS) are a form of agroforestry that integrates woody components (trees and/or shrubs), pastures, and livestock either directly or indirectly, aiming to generate ecological, productive, and environmental synergies (Murgueitio et al. 2011; Chará et al. 2019). There are various types of SPS, including systems with live fences, forage banks, intensive multistrata arrangements, and transitional systems, among others (Nair 1993; Sinclair 1999). These systems have emerged as a viable and sustainable alternative that aims to optimize livestock production and promote environmental conservation by integrating herbaceous, shrub, and perennial tree species (Navas-Panadero 2017). This combination of plant components provides benefits such as increased soil fertility, nutrient recycling, and reduced deforestation (Rivera et al. 2015; Fernández-Mayer 2017). Furthermore, including forage shrubs within SPS solves the limitations of conventional livestock systems related to forage quality and availability (Garrett et al. 2017; Bonilla-Cedrez et al. 2023). Therefore, the implementation of SSP is considered a sustainable livestock intensification practice that not only enhances ruminant feed supply but also seeks to restore degraded areas affected by extensive livestock farming and improve the resilience of production systems to climate change (Rao et al. 2015; Ku-Vera et al. 2020).

Recent studies have demonstrated that incorporating *Tithonia diversifolia* (Hemsl.) A. Gray into cattle diets improves nutritional quality, increases milk production, reduces enteric methane emissions, and enhances nitrogen balance, contributing to climate change mitigation (Fernández-Mayer 2017; Cardona-Iglesias et al. 2022; Rivera et al. 2022). Other shrubs, such as *Gliricidia sepium* (Jacq.) Kunth ex Walp. and *Guazuma ulmifolia* Lam., has been reported with high potential for improving forage quality and livestock system sustainability in acidic and degraded soils (Cabrera-Núñez et al. 2019; Argüello-Rangel et al. 2020a, b). Similarly, the nutrient and phytochemical contributions of shrubs such as *Piptocoma discolor* (Kunth) Pruski, *Clitoria fairchildiana*, and *Guazuma ulmifolia* can help improve nutrient supply, mitigate methane emissions, and contribute to carbon sequestration in tropical soils (Cabrera-Núñez et al. 2019; Narváez-Herrera et al. 2023).

In the Colombian Amazonian foothills, SPS represents a promising strategy for sustainably intensifying livestock production while addressing producers' needs and international environmental conservation commitments (Zapata-Cadavid and Silva-Tapasco 2020). Beyond ecological and productive gains, SPS offer a compelling economic rationale for producers, demonstrating enhanced profitability and monetary benefits that underscore their economic viability (Husak and Grado 2002; Junca Paredes et al. 2025). Understanding these multifaceted outcomes is crucial for regional sustainability, guiding extension programs, and shaping effective policy development in tropical livestock systems (Bussoni et al. 2019; Dollinger 2019; Stutzman et al. 2019).

However, despite the reported benefits, knowledge gaps persist regarding their specific impact on milk production and composition under local conditions (Fernández-Mayer 2017; Pezo 2017). Therefore, this study aimed to evaluate the productive, milk quality, and economic performance of dairy cows grazing in a silvopastoral system composed of *Piptocoma discolor* shrubs, *Erythrina poeppigiana, Clitoria*

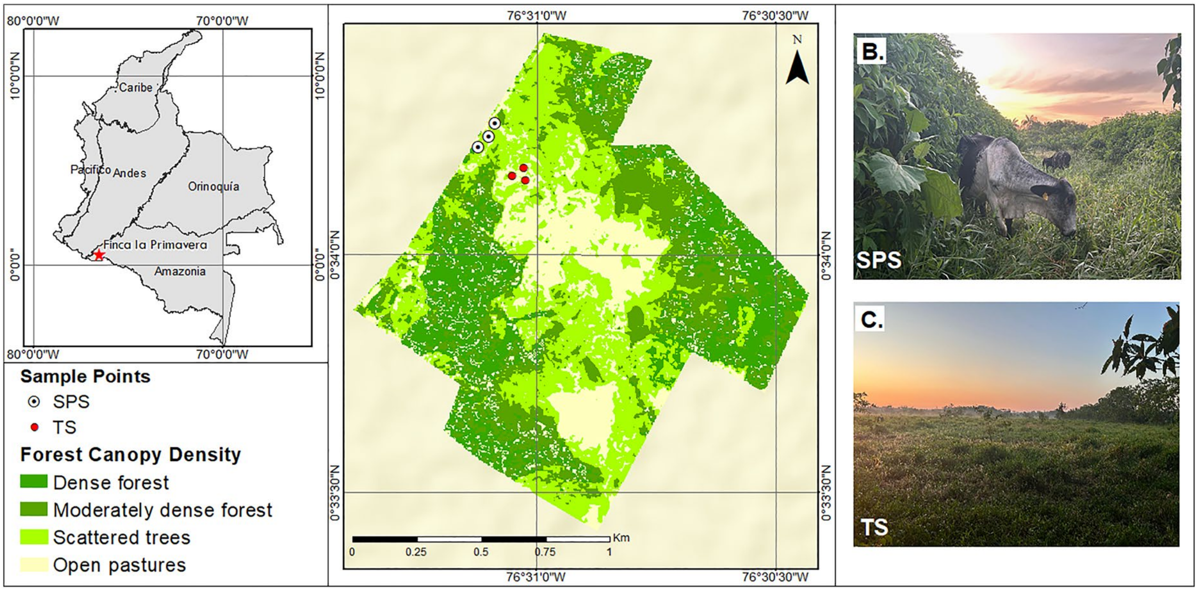

Fig. 1 **A** Geographical location of the experimental area. **B** Silvopastoral system (SPS) with *Piptocoma discolor* shrubs arranged in double rows for direct browsing, with *Urochloa decumbens* as the base pasture. **C** Pasture under traditional grazing system (TS)

fairchildiana, and *Guazuma ulmifolia* trees, and *Urochloa decumbens* grass, compared to a traditional grazing system in the Amazonian foothills.

Materials and methods

Study design

The study employed a crossover experimental design (Kung-Jong 2016) to evaluate two grazing systems. Two treatments were evaluated. The first treatment was a Silvopastoral System (SPS), composed of forage shrubs, trees, pasture, and cattle grazing directly on the paddocks. The *Piptocoma discolor* shrubs were planted at 6 m between rows and 0.5 m between plants, resulting in a density of 4,200 plants/ha. *Clitoria fairchildiana* and *Guazuma ulmifolia* trees were scattered throughout the pasture in a 20 m × 20 m grid, with a density of 25 trees/ha, while *Erythrina poeppigiana* trees were used as living fence, planted 6 m apart, with a density of 66 plants/ha. The base pasture in this system was *Urochloa decumbens*. At the time of evaluation, the system had been established for 18 months. Trees of *Erythrina poeppigiana* and *Clitoria fairchildiana* had reached heights of approximately 1.80–2.00 m, while *Guazuma ulmifolia* trees measured between 1.50 and 1.80 m. The second treatment was a traditional grazing system (TS) consisting of a *U. decumbens* monoculture managed under a 42-day rotational grazing cycle, with extensive management and low tree presence (< 25 trees/ha), primarily timber species (*Cordia alliodora*), aged 3–5 years, with a diameter at breast height of 30–40 cm.

Study site and experimental pastures

The study was conducted in the Aguanegra rural district, located in the municipality of Puerto Asís, Putumayo department, Colombia (0° 33′ 09″ N, 76° 30′ 55″ W), at an altitude of 270 m.a.s.l. (Fig. 1). The soils in the study area are classified as Ultisols (IGAC 2024), with a pH of 4.89. The experimental period lasted 76 days and was conducted during the transition from the rainy season to a period of lower precipitation (September–December 2024). The region has an average annual temperature of 29 °C, a relative humidity of 86%, and an average annual precipitation of 3,355 mm. According to Holdridge (1966), the experimental area belongs to a tropical humid forest life zone.

The experimental area for the evaluated treatments (SPS and TS) consisted of two hectares each, subdivided into daily grazing strips of 465 m^2, managed with electric fencing, to implement a rotational grazing system. This management involved a one-day occupation period and 42 days of rest for both pasture and shrubs, respectively. General microclimatic conditions of the experimental area (ambient temperature and relative humidity) were recorded during each measurement session using a portable weather station (Davis Vantage Pro2, Hayward, CA, USA).

Evaluated animals and experimental procedure

Ten lactating cows of undefined crossbreeding (*Bos taurus* × *Bos indicus*), from Holstein and Gyr breeds, were selected. The animals were chosen based on minimal variation in average milk production over the previous ten days, as well as similar milk protein and fat percentage, days in milk (DIM), number of calvings (NC), and body weight (BW) (Table 1). The selected cows were subsequently allocated into two homogeneous groups for use in the experiment. The evaluation lasted 76 days and was divided into four periods of 19 days each, 14 days of adaptation (Machado et al. 2016), and 5 days of evaluation. During the first period, one group of animals was randomly assigned to the SPS and the other to the TS. From the second to the fourth period, the groups were switched to the opposite treatment (Fig. 2).

Milking was performed manually twice daily at 04:00 and 14:00 h. The milking duration ranged from 5 to 8 min per cow. Cows were milked without the presence of their calves. This routine was maintained throughout the experimental period, using the same method and schedule for all animals. The characteristics of the animals in each treatment are presented in Table 1. In addition, all cows received 3.0 kg/day of commercial concentrate feed, divided into two portions of 1.5 kg, offered during each milking. This supplementation regime remained consistent throughout

Table 1 Characteristics of the animals and evaluation sequence assignment

Group	Weight (kg)	Number of calvings	Days in milk (DIM)	Milk production (L/cow/day)	Milk fat (%)	Milk protein (%)	Body condition score (BCS)
1	443 ± 21.35	3.2 ± 2.64	120 ± 32.86	14.2 ± 3.6	4.1 ± 0.07	3.34 ± 0.12	3.00 ± 0.25
2	462 ± 16.00	3.2 ± 1.60	126 ± 29.39	13.8 ± 1.6	4.0 ± 0.14	3.34 ± 0.14	3.25 ± 0.29

Values represent the means and standard deviations of the last ten days prior to the start of the experiment

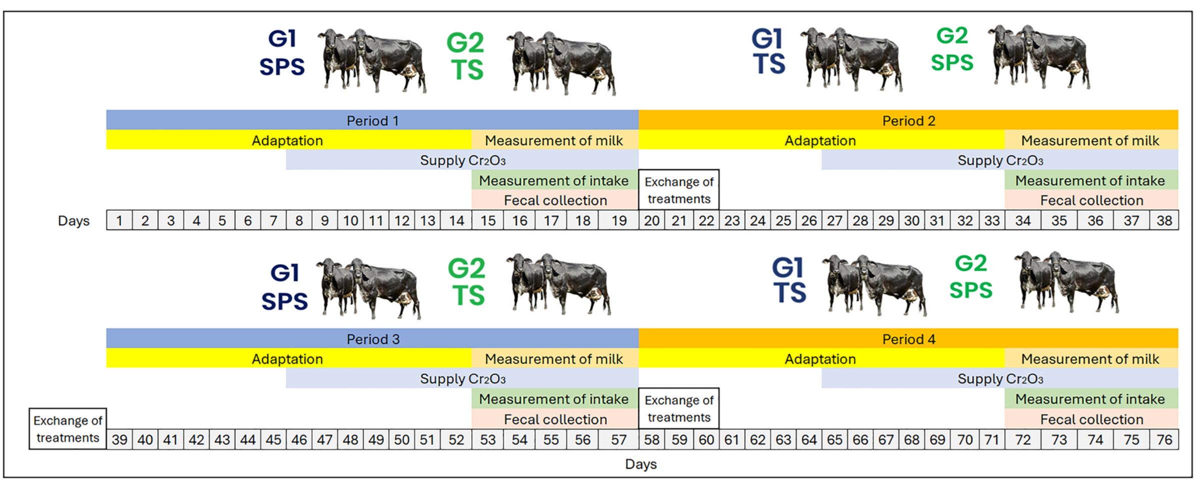

Fig. 2 Representation of the experimental design used for milk sampling, dry matter intake estimation using the marker method, Cr_2O_3 administration, and fecal collection. G1: Group 1 of animals; G2: Group 2 of animals; SPS: Silvopastoral system; TS: Traditional grazing system

Table 2 Nutritional composition of the evaluated species in the grazing systems

Variable	Silvopastoral System (SPS)			Traditional Grazing System (TS)	
	Concentrate Feed	*P. discolor*	*U. decumbens*	Concentrate Feed	*U. decumbens*
DM, %	87 ± 2.98	25.70 ± 1.53	23.0 ± 0.98	87 ± 2.98	22.85 ± 0.68
CP, %	16.02 ± 0.52	25.01 ± 0.69	9.79 ± 0.48	16.02 ± 0.52	8.64 ± 0.26
NDF, %	15.56 ± 0.54	50.01 ± 1.50	59.74 ± 3.01	15.56 ± 0.54	69.81 ± 4.10
ADF, %	7.62 ± 0.25	24.72 ± 1.23	31.87 ± 1.83	7.62 ± 0.25	37.08 ± 1.54
NEL, Mcal	1.89 ± 0.06*	1.49 ± 0.06	1.24 ± 0.09	1.89 ± 0.06[a]	1.10 ± 0.05
Available Biomass, kg DM/ha	–	802 ± 0.09	3958 ± 0.12	–	4074 ± 0.11

DM dry matter, *CP* crude protein, *NDF* neutral detergent fiber, *ADF* acid detergent fiber, *NEL* net energy for lactation

[a]NEL was estimated according to Buxadé (1995) using the equation NEL = 0.677 × DE − 0.359, where DE = digestible energy (kcal/kg). Available biomass values represent the mean pre-grazing forage mass per hectare on a dry matter basis during the experimental period, including standard deviation

the experimental period. The nutritional composition of the concentrate is presented in Table 2.

Nutritional composition of the species used in the study

The nutritional composition (dry matter [DM], crude protein [CP], neutral detergent fiber [NDF], acid detergent fiber [ADF], net energy for lactation [NEL]) of *Urochloa decumbens* in both systems and *Piptocoma discolor* in the SPS was evaluated at 42 days of regrowth. Forage sampling was conducted during the pre-experimental period using the agronomic method adapted from Haydock and Shaw (1975), as described by Angulo-Arizala et al. (2022). The percentage of shrub inclusion in the SPS was estimated by measuring forage biomass before and after grazing in four independent paddocks, using 1 m^2 quadrats at four representative locations per paddock. Samples were hand-cut at 5 cm above ground level, separated by species group (grass or shrub), oven-dried at 60 °C to constant weight, and expressed in kg of DM/ha. This procedure allowed the estimation of the biomass contribution of each forage type to the diet. Based on these measurements, the average forage biomass ratio in SPS was 12% *P. discolor* and 88% *U. decumbens*. During the evaluation phase, the grazing area was adjusted based on forage availability, animal number, and body weight, ensuring consistent forage and species composition intake across periods. All forage samples were ground using a 1-mm mesh hammer mill and analyzed by near-infrared spectroscopy (NIRS) according to Ariza-Nieto et al. (2018), at the Agrosavia laboratories (Mosquera, Colombia). Although *Clitoria fairchildiana, Guazuma ulmifolia,* and *Erythrina poeppigiana* were present in the silvopastoral paddocks, their direct contribution to animal intake was not quantitatively measured in this study, as the study's primary focus was on the nutritional contribution of *Piptocoma discolor*, identified as the dominant browsed shrub species. Nevertheless, consistent with their established role as tree components, their presence offered benefits such as shade provision, soil improvement, and enhanced animal welfare within the SPS, rather than serving as primary forage sources. Therefore, only the nutritional composition of Piptocoma discolor, the dominant and directly browsed shrub species, was analyzed and included in Table 2.

Evaluated variables

Estimation of forage dry matter intake (DMI)

Forage dry matter intake (DMI) was estimated using the double marker method, combining chromium oxide (Cr_2O_3) as an external marker and acid detergent lignin (ADL) as an internal marker, as described by Lachmann-Sevilla et al. (2003) and Correa et al. (2009). Chromium oxide was administered orally at a total dose of 30 g/cow/day during each experimental period, divided into two equal portions (15 g) offered at morning and afternoon milking, over 12 consecutive days. The first seven days were used for adaptation, while fecal samples were collected from days 8 to 12. The Cr_2O_3 content in feces was used to estimate total fecal output, following the complete fecal collection method described by Correa et al. (2009). To distinguish between forage and supplement intake, the internal lignin marker (ADL) was analyzed in feces, forage, and concentrate samples. The differential lignin content allowed partitioning of total dry matter intake into forage and supplement fractions. The following equation was used to estimate DMI (Mejía-Díaz et al. 2017):

$$DMI = \frac{(\%LigH \times FO) - (\%LigC \times CI)}{\%LigF} \quad (1)$$

where: FO = total fecal output (g/day); %LigH = lignin concentration in feces; %LigC = lignin in concentrate feed; CI = concentrate intake (g/day); %LigF = lignin in forage. Fecal samples were collected using harnesses equipped with fecal collection bags, which allowed partial recovery of the excreted chromium oxide. The bags were emptied twice daily to minimize sample loss and maintain sample integrity. Prior to the main trial, the chromium recovery rate was experimentally determined using three lactating cows that received chromium oxide following the protocol described by Correa et al. (2009). Chromium concentrations in feces were quantified by atomic absorption spectrophotometry, and the recovery rate calculated as the ratio of excreted to administered chromium was 79.8%. This value was subsequently used to correct total fecal output and refine estimates of individual dry matter intake (DMI).

Milk production and composition

Milk production (kg/day) was measured individually and directly from the milking bucket. For compositional analysis, milk was homogenized using a collection cup, ensuring no foam was generated. Subsequently, a 25 mL sample was taken from the bottom of the container during the morning milking and another 25 mL sample during the afternoon milking. Composite milk samples were obtained by pooling individual samples collected during the first three days (days 1–3) and separately during the last two days (days 4–5) of each evaluation period. This approach was used to account for potential within-period variability in milk composition due to environmental and physiological factors. Two composite samples were thus generated per cow in each period, ensuring representative analysis. This sampling strategy followed the methodology described by Angulo-Arizala et al. (2021). The composite samples were sent to the Milk Composition Laboratory at the University of Antioquia (Medellín, Colombia), using bronopol as a preservative (Mitul et al. 2020). Milk composition variables including protein (%), fat (%), lactose (%), milk urea nitrogen (MUN, mg/dL), and total solids (%), were determined using a MilkoScan FT + milk analyzer (Foss, Hillerød, Denmark). Milk volume (in liters) was converted to kilograms using an average milk density of 1.032 g/mL, as established by the Codex Alimentarius (FAO/WHO 1999). Subsequently, milk production was adjusted to 4% fat-corrected milk (FCM) using the equation proposed by NRC (2001) (Eq. 2), to allow meaningful comparisons between treatments. Fat yield, protein yield, lactose yield, and total solids yield (kg/day) were calculated by multiplying daily milk production (kg/day) by the corresponding proportion of each component, as described by Angulo-Arizala et al. (2022). Fat- and protein-corrected milk yield (FPCM, kg/cow/year) was calculated following IDF (2015), using Eq. (3).

$$FCM\ (\text{kg/day}) = (0.4 \times milk\ yield) + (15 \times \text{fat yield}) \quad (2)$$

$$FPMC\ (\text{kg/year}) = production\ (\text{kg/year}) * \left[0.126 * milk\ fat\% + 0.0776 * milk\ protein\% + 0.2534\right] \quad (3)$$

Experimental design and statistical analysis

A crossover design (Kung-Jong 2016) was employed; this experimental design has been used in animal science, as it avoids time- and experimental unit-consuming factors (Machado et al. 2016), resulting in a suitable design for in-livestock farm experimental conditions (Engstrom et al. 2010; Lahlou et al. 2014; Barragán-Hernández et al. 2020; Loza et al. 2021; Lopera et al. 2025). Each group of animals (G1 and G2) was randomly assigned to the grazing systems (SPS and TS), with defined adaptation and evaluation periods. Each cow within each group was considered the experimental unit. Data were analyzed using a mixed model, employing the *lmer* package from the *lme4* library (Bates et al. 2015) in the R-Project statistical software, version 4.3.1. For milk compositional variables (fat, protein, milk urea nitrogen [MUN], and lactose) and forage dry matter intake (DMI, dry basis), the analysis considered treatment (SPS and TS) as a fixed effect, and animal within the group and period as random effects. Regarding productive variables (milk yield [kg/day] and fat-corrected milk yield), the analysis considered evaluation day and treatment-by-day interaction as fixed effects, and animal and period as random effects. Days in milk, the number of calvings, body weight, and body condition, were collected before the experiment were used as covariates. Body condition score (BCS) was evaluated according to Edmonson et al. (1989). Tukey's test was used for mean separation analysis when significant differences were found.

Economic analysis

The production cost per kilogram of milk was calculated for each system, and the percentage distribution of the cost components was determined. This analysis considered the implementation, establishment, fertilization, and management costs for both the SPS and TS. Fixed costs included milking labor, depreciation of facilities and equipment, water consumption, and property tax. Variable inputs considered in the analysis included supplements, medications, fuel, electricity, and repairs. The Quick Cost Tool for Dual-Purpose and Beef Cattle Milk Production Systems (Botero and Rodríguez 2006) was used for cost estimation. The total values were divided by the daily milk production per animal to obtain the cost per liter of milk, as described by Angulo-Arizala et al. (2021). Milk composition and the raw milk payment system for suppliers, established by Resolution 000017 of 2012 from the Ministry of Agriculture and Rural Development (MADR 2012) of Colombia, were considered to calculate the payment per kilogram of milk. The selling price per kilogram of milk was then multiplied by the kilograms of milk produced per cow per day to calculate the total daily income per cow from milk sales.

To evaluate the financial performance of the SPS and the TS, a discounted cash flow analysis was conducted over an 8-year time horizon. The analysis included standard investment appraisal indicators: Net Present Value (NPV), Benefit–Cost Ratio (B/C), and Payback Period (PB).

The NPV was calculated using the following Eq. (4):

$$NPV = \sum_{t=1}^{T} \frac{NCFt}{(1+r)^t} - I_0 \quad (4)$$

where: $NCFt$ is the net cash flow in year t (income minus costs), r is the discount rate (set at 8%), I_0 is the initial investment, T is the evaluation period (8 years). The Benefit–Cost Ratio (B/C) was estimated as the ratio of the present value of total benefits (PVB) to the present value of total costs (PVC), using the Eq. (5); values of B/C greater than 1 indicate that the system is economically viable.

$$B/C = \frac{PVB}{PVC} \quad (5)$$

The Payback Period (PB) represents the number of years required for the cumulative net cash flows to recover the initial investment. In this study, it was calculated by identifying the first year in which the accumulated net cash flows equaled or exceeded the initial outlay, following the procedure described and applied by Junca-Paredes et al. (2025).

The stocking rate, expressed as animal units per hectare (AU/ha), was used to estimate the total annual milk production per hectare in each system. This parameter, combined with individual milk yield, allowed the calculation of gross income per hectare per year from milk sales. The resulting stocking rates were then used to project annual milk production and gross income per hectare for each system. The stocking rate was estimated based on the apparent dry matter (DM) intake per hectare per day, obtained in each grazing system during the adaptation period, using the agronomic method described by Haydock and Shaw (1975). This method involved measuring forage availability before and after a 24-h grazing period using 1 m^2 quadrats to determine the apparent fresh forage consumption. The difference between both measurements was converted to dry matter using the pasture's DM content and adjusted by a 30% loss due to wastage. Subsequently, the apparent DM consumption per hectare was divided by the individual daily DMI to calculate the stocking rate, expressed as animal units per hectare (AU/ha). This procedure was applied independently to the SPS and the TS, based on their respective forage availability and the measured DMI values. The resulting stocking rates were then used to project the annual milk production and gross income per hectare for each system.

Results

Forage dry matter intake (DMI) and nutrient intake

DMI showed differences between the evaluated systems. Table 3, animals grazing in the SPS consumed more dry matter than those in the TS ($p<0.001$). When expressed as a percentage of body weight, DMI in the SPS was also greater compared to the TS ($p<0.001$). Consistent with the greater DMI, CPI and NEL intake were also greater in the SPS ($p<0.001$). In contrast, no differences were observed in the intake of neutral detergent fiber (NDFI) or acid detergent fiber (ADFI) ($p>0.05$). Detailed information on the dry matter intake and nutrient contribution from each diet component is presented in Supplementary Table S1.

Milk production and composition

Milk yield was greater in the SPS compared to the TS ($p<0.001$), both in raw milk yield and in 4% fat-corrected milk (FCM). Feed efficiency (FE), expressed as kilograms of milk per kilogram of dry matter intake, was also greater in the SPS ($p<0.001$). Energy efficiency (EE), defined as megacalories per kilogram of milk produced, was better in the SPS ($p<0.001$) (Table 4). Among the covariates included in the statistical model, body weight (BW) significantly influenced milk yield ($p=0.009$), FCM ($p=0.015$), FE ($p=0.008$), and EE ($p=0.011$). Other covariates, such as body condition score (BCS), number of calvings (NC), and days in milk (DIM), showed no consistent effects on these specific parameters.

There were no differences observed for fat, protein, fat-to-protein ratio (F:P), total solids, or lactose ($p>0.05$). However, milk urea nitrogen (MUN) was greater in the SPS ($p<0.001$). Component yields, including daily production of fat, protein, total solids, and lactose, were greater in the SPS ($p<0.05$). Similarly, the annual fat- and protein-corrected milk yield (FPCM) was greater in cows under the SPS ($p<0.001$) (Table 4). Among the covariates, BW significantly affected fat yield ($p=0.028$), protein yield ($p=0.005$), total solids yield ($p=0.006$), lactose yield ($p=0.010$), and annual fat- and protein-corrected milk yield (FPCM; $p=0.012$). Additionally, body condition score significantly influenced milk protein percentage ($p=0.042$). Other covariates (NC and DIM) generally did not show a significant effect on the analyzed variables ($p>0.05$).

Table 3 Dry matter intake and estimated nutrient consumption by experimental animals in the silvopastoral system (SPS) and traditional grazing system (TS)

	DMI (kg/animal/day)	DMI (% BW)	CPI (kg/animal/day)	NDFI (kg/animal/day)	ADFI (kg/animal/day)	NEL intake (Mcal/animal/day)
SPS	12.9 ± 0.12	2.91 ± 0.15	1.61 ± 0.009	6.43 ± 0.05	3.34 ± 0.03	18.00 ± 0.10
TS	10.5 ± 0.12	2.33 ± 0.12	1.10 ± 0.009	5.91 ± 0.05	3.12 ± 0.03	13.61 ± 0.10
p-value	0.001	0.001	0.001	0.863	0.771	0.001

SPS silvopastoral system, *TS* traditional grazing system, *DMI* dry matter intake, *BW* body weight, CPI crude protein intake, *NDFI* neutral detergent fiber intake, *ADFI* acid detergent fiber intake, *NEL* net energy for lactation intake

Table 4 Milk production parameters, composition (percentage and component yields), efficiency, and fat- and protein-corrected milk (FPCM) in dairy cows managed under silvopastoral (SPS) and traditional grazing systems (TS)

Variable	SPS	TS	RMSE	*p* value treatment
Milk production and efficiency				
Milk yield (kg/day)	14.13 ± 0.80	12.92 ± 0.80	1.79	0.001
4% FCM (kg/day)	14.10 ± 0.76	12.90 ± 0.76	2.04	0.001
FE (kg milk/kg DM)	1.24 ± 0.07	1.17 ± 0.07	0.157	0.001
EE (Mcal/kg milk)	0.675 ± 0.04	0.781 ± 0.04	0.109	0.001
Milk composition, %				
Fat (%)	4.00 ± 0.19	4.04 ± 0.19	0.325	0.597
Protein (%)	3.25 ± 0.09	3.26 ± 0.09	0.062	0.501
Ratio F:P	1.23 ± 0.04	1.24 ± 0.04	0.111	0.731
Total solids (%)	12.5 ± 0.28	12.6 ± 0.28	0.418	0.312
Lactose (%)	4.71 ± 0.07	4.73 ± 0.07	0.057	0.296
MUN (mg/dL)	11.9 ± 2.26	10.2 ± 2.26	1.749	0.001
Milk composition, kg				
Fat (kg)	0.560 ± 0.03	0.513 ± 0.03	0.093	0.0001
Protein (kg)	0.455 ± 0.02	0.423 ± 0.02	0.069	0.0001
Total solids (kg)	1.76 ± 0.09	1.61 ± 0.09	0.247	0.0001
Lactose (kg)	0.667 ± 0.03	0.605 ± 0.03	0.083	0.0001
FPCM (kg^{-1}/$año^{-1}$)	4322 ± 232	3969 ± 232	618	0.0001

SPS: silvopastoral system; TS: traditional grazing system. RMSE: root mean square error. Milk yield (kg/day): daily milk production per cow; 4% FCM: fat-corrected milk standardized to 4% fat; FE: feed efficiency (milk yield/DMI); EE: energy efficiency (milk energy output/energy intake); MUN: milk urea nitrogen; FPCM: fat- and protein-corrected milk yield. Daily yields of milk components (fat, protein, total solids, lactose in kg) were calculated as the product of milk yield (kg/day) and the corresponding component percentage. Values are expressed as mean ± standard deviation (SD)

Table 5 Economic performance indicators of dairy systems managed under silvopastoral (SPS) and traditional grazing (TS) conditions

Indicator	SPS	TS
Implementation cost per ha (USD)	2240.85	501.65
Production cost per kg of milk (USD)	0.37	0.36
Milk production (kg/cow/day)	14.3	12.92
Production cost per cow (USD)	5.43	4.69
Selling price (USD/kg milk)	0.68	0.68
Revenue per cow per day (USD)	9.73	8.79
Stocking rate, AU/ha	2.89	1.63
Milk production (kg/ha/year)	12.605	6.423
Revenue per hectare per year (USD/ha/year)	8.573	4.368
Net present value (NPV) (USD)	13.581	1.250
Benefit–cost ratio (B/C)	2.05	1.115
Payback period (years)	3.5	8.7

USD values were calculated by dividing the COP values by the TRM of 4.116,61 COP/USD

Economic analysis

The economic analysis revealed a clear advantage of the SPS over the TS in terms of productivity and profitability (Table 5). Although SPS required a greater initial investment per hectare, this was offset by the increased milk yield per cow and a greater stocking potential, resulting in increased annual production and income per unit area. The estimated stocking rate, based on the agronomic method described in the methodology, was 2.5 animal units (AU)/ha for SPS and 1.8 AU/ha for TS. These values were incorporated into the economic model to project milk production and income per hectare. Despite a slightly greater production cost per kilogram of milk in the SPS, the system achieved superior financial performance, as evidenced by a greater benefit–cost ratio (B/C), greater net present value (NPV), and shorter investment payback period.

Discussion

Dry matter intake (DMI) and nutrient intake in a silvopastoral system (SPS) and a traditionally managed pasture (TS)

The findings of this study agree with reports indicating that SPS provide greater-quality forage in greater available biomass, promoting greater voluntary intake by animals (Cuartas-Cardona et al. 2015). Studies conducted in the northern highlands of Antioquia with Holstein cows found that DMI in an SPS with *Tithonia diversifolia* and *Cenchrus clandestinum* reached values up to 14.7 kg/cow/day, confirming that forage availability and composition in these systems favor greater intake (Mejía-Díaz et al. 2017). Similarly, López-Ortiz et al. (2021) evaluated foraging behavior in sheep and found that the presence of trees and shrubs influences forage selection and intake efficiency, depending on shade availability and resource distribution. Additionally, trees and shrubs in the SPS provide shade, reducing heat stress, which may contribute to greater voluntary feed intake (González-Quintero et al. 2024). Under humid tropical conditions, DMI in an SPS with *Tithonia diversifolia* and *Urochloa brizantha* cv. Toledo associated with *Urochloa humidicola* in BON × Zebu heifers were reported at 4.3 kg/animal/day, while in a monoculture system, it was 4.09 kg/animal/day (Argüello-Rangel et al. 2020a, b), suggesting that SPS create favorable conditions to enhance animal productivity. During the experimental period, the general microclimatic conditions were characterized by an ambient temperature of 31.96 ± 2.45 °C and a relative humidity of 85.39 ± 0.72%. These conditions are typical of humid tropical environments, where heat stress can significantly influence animal intake and performance (González-Quintero et al. 2024).

In our study, the silvopastoral system was characterized during the pre-experimental phase, with a shrub-to-grass consumption ratio of 12:88 (*Piptocoma discolor*: *Urochloa decumbens*). Despite the predominance of grass in the forage base, the structured inclusion of *P. discolor* provided a consistent protein-rich component that likely stimulated greater voluntary DMI in the SPS. Consistent with these observations, DMI as a percentage of body weight (BW) was greater in the SPS compared to the TS. This finding aligns with a showing average DMI of 2.65% BW for unsupplemented and 2.88% BW for supplemented grazing dairy cows in the tropics (Boval and Sauvant 2019). The lower DMI (% BW) in the TS can be attributed to its *Urochloa decumbens* pasture's greater concentrations of NDF and ADF compared to SPS forages. High fiber content is known to limit dry matter intake due to increased rumen fill and slower passage rates (Van Soest 1994). Such effects align with findings from silvopastoral systems incorporating shrubs like *Tithonia diversifolia*, which have shown similar effects on intake and overall dietary balance (Mejía-Díaz et al. 2017; Lopera-Marín et al. 2025).

The crude protein intake (CPI) and net energy for lactation intake (NEL) were greater in the SPS compared to the TS. This result is consistent with findings by Rivera et al. (2015), who reported a 6.71% increase in milk production in an SPS with *Tithonia diversifolia* in the Amazonian foothills, attributed to improved dietary protein and energy availability. In our study, the greater CPI (1.61 kg/animal/day) meets and even exceeds the values recommended for medium-producing cows (8–10 kg of milk/day), which range from 1.4 to 1.6 kg/day according to NRC (2001). Similarly, NEL intake in the SPS reached 18.0 Mcal/animal/day, aligning with the estimated requirements of 17.5–19.5 Mcal/day for this animal type, indicating an adequate energy supply essential for maintaining efficient production. These results agree with those of Sierra-Montoya et al. (2017), who reported a positive nutritional balance in *Gyr × Holstein* cows managed in an intensive SPS with *Leucaena leucocephala* and *Cynodon plectostachyus,* supplemented with concentrate; in contrast, grass-only diets were often insufficient to meet the animals' full nutritional demands. In our case, although both systems received the same concentrate supplementation, the inclusion of *Piptocoma discolor* in the SPS contributed a protein- and energy-rich component that enhanced the overall nutritional profile of the diet. This additional input likely supported key physiological functions such as body condition recovery, reproductive activity, and productive stability (Ibrahim et al. 2006). The silvopastoral system also showed a lower energy requirement per unit of milk produced (0.675 Mcal/kg of milk) compared to the traditional pasture system (0.781 Mcal/kg of milk). Since energy efficiency is defined as the amount of energy required to produce one kilogram of milk, these findings suggest that cows under SPS conditions converted dietary energy into milk more efficiently, resulting in increased productivity with reduced nutritional energy input.

Similar to our study using a different *Asteraceae* species, Angulo-Arizala et al. (2022) reported that the inclusion of *Tithonia diversifolia* in the diets of Holstein cows improved both feed and energy efficiency, associated with greater nutrient intake and enhanced productive performance. Moreover, Mejía-Díaz et al. (2017) observed greater dry matter intake in SPS with *T. diversifolia*, which was related to improved forage quality and availability. These findings are consistent with those of Ramírez-Avilés et al. (2007), who emphasized that the foliage of tropical shrubs provides rapidly available nitrogen, which promotes increased microbial protein synthesis and enhances ruminal degradation efficiency. The results obtained in the present study reinforce the hypothesis that SPS not only improve forage supply but also contribute to the animals' nutritional balance, which can lead to substantial improvements in productive and reproductive performance under tropical conditions.

Milk production and composition

The results of this study indicate that milk production was greater in the SPS compared to the TS, both for unadjusted milk yield and 4% fat-corrected milk. Our findings are consistent with previous studies (Rivera et al. 2015; Barragán-Hernández et al. 2016; Cardona-Iglesias et al. 2022), which demonstrate that the integration of forage shrubs and trees in SPS enhances nutritional availability and leads to greater productive performance. In our study, milk production in the SPS was 14.13 kg/cow/day, whereas in the TS, it was 12.92 kg/cow/day, representing a 9.37% increase in milk production. Similar values have been reported in the Colombian Amazonian foothills, where milk production in an SPS with *Tithonia diversifolia* exceeded that of conventional systems by 6.71% (4.92 kg/cow/day in SPS vs. 4.59 kg/cow/day in traditional grazing systems) (Rivera et al. 2015). Similarly, Mavisoy et al. (2025) found that on farms with high SPS adoption, fat- and protein-corrected milk (FPCM) production reached 6056.7 kg/cow/year, greater than the 2883.0 kg/cow/year observed on farms with low SPS adoption.

Feed efficiency (FE), expressed as the amount of milk produced per unit of dry matter consumed, was also greater in the SPS (1.23 kg of milk/kg DM) compared to the TS (1.13 kg of milk/kg DM), indicating a more efficient utilization of consumed nutrients by cows in this system. The FE reported in this study was consistent with Angulo-Arizala et al. (2022), who found that including *Tithonia diversifolia* in the diet increased feed efficiency by 10–15%, due to an improved protein-energy balance, which optimizes ruminal fermentation and nutrient conversion efficiency, favoring microbial protein synthesis and nitrogen retention in animal metabolism (Rivera et al. 2015). Additionally, Galindo et al. (2022) reported that including *Tithonia diversifolia* in the diet increased the populations of cellulolytic and proteolytic bacteria in the rumen, improving fiber degradation, ammonia conversion into microbial protein, and energy efficiency, while also reducing methane production. Our results suggest that due to its crude protein content, *Piptocoma discolor* (Álvarez-Carrillo et al. 2022) may exert similar effects on ruminal fermentation and feed efficiency.

Milk composition did not differ between treatments for fat, protein, total solids, and lactose content, suggesting that the feeding system did not affect these parameters as reported by Rivera et al. (2015) who found similar fat and protein values in SPS and conventional systems (3.39% and 3.35%, respectively). Regarding milk urea nitrogen (MUN), greater concentrations were observed in the silvopastoral system (11.9 mg/dL) compared to the traditional pasture (10.2 mg/dL). Under tropical conditions, MUN levels in dual-purpose cows (crossbreeds of Brahman, Holstein, and Gyr) have been reported between 4 and 17 mg/dL. For instance, Pozo-Leyva et al. (2024) found MUN values between 8.4 and 9.7 mg/dL in Brahman × Gyr × Guzerat cows fed local diets in sub-humid Mexican tropics. Similarly, Durango-Morales et al. (2021) reported a wider range of 4.4–17.2 mg/dL in *Bos indicus* crossbreds in Colombia, with the highest value associated with protein-supplemented diets. Letelier et al. (2022), in a multisite study in Costa Rica, reported average MUN concentrations of 12.6 mg/dL in conventional systems and 11.8 mg/dL in silvopastoral systems. Researchers suggest that an appropriate MUN range is between 8 and 14 mg/dL. They emphasize that when MUN levels fall outside this range, dietary protein and energy sources should be evaluated (Wattiaux and Ranathunga 2016). Elevated MUN concentrations may indicate an imbalance between rumen-degradable protein and fermentable energy availability, limiting microbial nitrogen utilization and increasing nitrogen excretion via milk and urine (Juárez-Lagunes et al. 1999).

In the present study, MUN values from both treatments were within the suggested optimal range. However, the slightly greater levels observed in the silvopastoral system may reflect greater protein intake due to the inclusion of shrubs and concentrate supplementation, resulting in a greater total protein supply relative to available energy. Variability in MUN responses across studies may be explained by differences in forage proportions, diet composition, and energy-to protein ratios. Nevertheless, the inclusion of high-protein shrubs in diverse SPS has shown potential to enhance microbial protein synthesis and improve nitrogen utilization efficiency, thereby supporting both productive performance and environmental sustainability in tropical livestock systems (Angulo-Arizala et al. 2022; Bottini-Luzardo et al. 2016; Pozo-Leyva et al. 2024).

Fat- and protein-corrected milk (FPCM) production was 8.9% greater in the SPS compared to the TS, suggesting improved nutrient utilization and efficiency in milk solids synthesis. In a related study, Mavisoy et al. (2025) reported that dual-purpose farms implementing technified silvopastoral systems achieved FPCM yields 12.1% greater than transitional farms, indicating that the degree of system development and management practices can substantially influence productivity. Additionally, supplementation with *Tithonia diversifolia* increased FPCM production by 11% during the moderate rainfall season and by 7% during the heavy rainfall season, highlighting its potential to improve production efficiency in SPS (Rivera et al. 2022).

Economic analysis

The economic analysis shows that, despite requiring considerably greater initial investment compared to TS, the SPS demonstrates superior profitability and more efficient financial performance in the medium term. The greater stocking rate and increased individual productivity are reflected in greater annual milk production per hectare and, consequently, greater gross annual income per unit area. Although the cost of milk production per kilogram was 4.08% greater in the SPS compared to the TS, the financial analysis demonstrates a favorable benefit–cost ratio (B/C) for the SPS, with a value of 2.05 compared to 1.115 in the TS. This indicates that for every unit invested in the SPS, a total return of 2.05 units is generated—equivalent to recovering the investment and obtaining a net gain of 1.05 units, which represents a substantially greater return than that obtained in the traditional system. Positive economic analysis has been reported by Cuevas-Reyes et al. (2020), indicating B/C ratios greater than 1.2 in irrigated silvopastoral systems, with attractive returns starting in the second year of implementation. Similarly, Gallego-Castro et al. (2017) reported a benefit–cost ratio of up to 4.60 when incorporating *Tithonia diversifolia* into dairy cow diets; however, it is important to note that their calculation focused exclusively on feeding costs and milk revenue, without accounting for total production costs. In this context, despite greater initial investment and operational costs, SPS can provide substantial advantages in terms of improved feed conversion efficiency and stable production throughout the year (Murgueitio-Restrepo et al. 2016; Rivera-Herrera et al. 2017).

The estimated net present value (NPV) for the SPS was greater than that of the TS, while the investment payback period was considerably shorter (3.5 years vs. 8.7 years) respectively. Although the implementation cost per hectare was considerably greater in the SPS compared to the TS, this investment was mainly due to the establishment of shrub and tree components, including planting, labor, maintenance, and fencing. These fixed costs initially increased the outlay but contributed to improved forage availability and intake over time. The enhanced productivity per animal and greater stocking rate in SPS resulted in greater daily milk production, and consequently, more significant annual revenue per hectare. This increased cash flow explains the shorter payback period observed in SPS (3.5 years) compared to TS (8.7 years), despite the initial investment being more than four times greater. Therefore, the greater upfront cost in SPS was rapidly offset by improved biological and economic performance. The profitability reported in this study aligns with the findings of Zambrano-Yepes et al. (2024), who indicated that silvopastoral models in the northwestern Colombian Amazon recover their investment between the second and third year, due to the progressive reduction in supplementation costs and increased forage use efficiency (Alonso 2016). Similarly, Junca

Paredes et al. (2025) evaluated an intensive SPS in San Martín, Peru, and reported a benefit–cost ratio of 1.634 and a payback period of 4.55 years. Despite high implementation costs primarily related to the establishment of tree and live fence components economic viability was achieved through enhanced forage utilization, increased milk yields, and stronger revenue flows. Moreover, their study emphasized the importance of complementary financial instruments such as payments for ecosystem services and tailored credit schemes in facilitating SPS adoption by smallholder farmers. These findings reinforce the economic robustness of SPS under diverse tropical conditions. The economic results in this study highlight the potential of SPS to deliver sustainable economic benefits in the medium term (Rade et al. 2017; Ramírez-Flores et al. 2022). It is worth noting that, although the initial investment and operational costs of SPS may pose a barrier for small-scale producers with limited financial resources, financial strategies such as agricultural credit, government incentives, payments for ecosystem services, and premium pricing programs based on quality or environmental certification can facilitate adoption. In this regard, SPS represents not only a productive intensification strategy and an environmentally sustainable approach, but also a financially sound alternative that contributes to the economic resilience of livestock systems under tropical conditions.

Conclusions

The integration of *Piptocoma discolor* shrubs and multipurpose tree species (*Erythrina poeppigiana*, *Clitoria fairchildiana*, and *Guazuma ulmifolia*) with a base pasture of *Urochloa decumbens* into a silvopastoral system significantly improved the productive and economic performance of dairy cows in the Amazonian foothills compared to a traditional pasture system. The silvopastoral system enhanced dry matter intake, milk yield, and nutritional efficiency, evidenced by lower energy expenditure per kilogram of milk and an adequate protein and energy balance. While milk composition remained unchanged, greater milk urea nitrogen levels indicated a greater protein supply associated with the diverse forage mix. Despite requiring a greater initial implementation cost and resulting in a modest increase in production cost per liter of milk, the SPS exhibited superior economic outcomes. These included a greater benefit–cost ratio, greater net present value, and a notably shorter investment payback period. These findings suggest that native shrubs like *P. discolor* can contribute to the sustainable intensification of livestock systems in tropical regions, offering both nutritional and financial benefits. Broader adoption, however, will necessitate supportive public policies, improved access to financing, and targeted technical assistance, particularly for small and medium-scale producers.

While this study provides valuable insights, its limited evaluation period (76 days) means the results should be considered preliminary and indicative of potential benefits. Long-term studies are essential to fully assess system stability, sustainability, and seasonal variability. Nevertheless, these findings align with observations from long-term SPS research (e.g., studies spanning over a decade in high tropical areas and more than two decades in lowland tropics) that utilized other shrub and tree species. Crucially, this study represents the first evaluation of an SPS integrating P. *discolor, E. poeppigiana, C. fairchildiana*, and *G. ulmifolia* under the specific conditions of the Amazonian foothills, thus highlighting the need for continued research to confirm its long-term viability and broader applicability.

Future research should extend to long-term evaluations of environmental indicators, such as carbon sequestration, greenhouse gas mitigation, and climate variability resilience. The integration of native forage shrub species into silvopastoral systems presents a promising strategy toward productive, climate-smart, and environmentally responsible livestock production in tropical regions.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no conflicts of interest. The funding sources was not involved in the study design; data collection, analysis, or interpretation; manuscript writing; or the decision to publish the results.

Consent to participate Not applicable.

Consent for publication Not applicable.

Ethical approval The procedures described in this study were conducted following protocols approved by the Ethics Committee for Animal Experimentation (CEEA) at the University of Antioquia under Act No. 0146 of June 7, 2022, ensuring animal welfare. This manuscript does not include clinical studies or patient data.

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