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RESEARCH PAPER

Comparison of different models to describe the lactation curve of Holstein cows in a small-scale dairy system

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Abstract

Modeling lactation curves with mathematical equations is useful to describe and predict the productivity of dairy cows. However, studies analyzing the performance of different models to describe lactation curves in small-scale dairy systems are sparse. Therefore, the objective of this study was to evaluate the capacity of five models to describe lactation curves of cows in a small-scale dairy system. Monthly milk weighins from 936 lactations were conducted in 23 farms in western Mexico. The Bayesian information criterion (BIC) and mean square prediction error (MSPE) were used to assess the fit of the models to the observed data, and the root mean square prediction error as a percentage of the observed mean (%RMSPE) was used to evaluate the accuracy of the models. The Gaines model had the best fit (lowest BIC and MSPE) for the first, second, and third or higher lactations. Regarding accuracy, the Sikka and Gaines models had the lowest RMSPE and %RMSPE. When classified by production level, the Gaines model had the best fit. The Gaines and Sikka models had the best accuracy across all three production levels. It was concluded that the Gaines model is the best option for representing lactation curves in a small-scale milk production system.

Keywords

Gaines model, lactation curves, modeling, Sikka model

Introduction

Family-based, semi-technified, or small-scale production system contributes to approximately one-third of milk production in Mexico (Plata-Reyes et al. 2018). Of the country´s production units, 73% operate under semi-mechanized conditions, and approximately 25% are small-scale dairy farms (Plata-Reyes et al. 2018). In addition to its contribution to national production, small-scale systems enhance food security and improve the nutritional quality of diets in rural families. The economic income they generate also encourages greater attachment of residents to their places of origin, helping to mitigate migration (Espinoza-Ortega et al. 2005). However, the survival of these farms is at risk due to production inefficiencies that compromise their sustainability (Posadas-Domínguez et al. 2014; Montiel-Olguín et al. 2019). To design strategies for improvement, it is necessary to analyze the productive performance of cows under these management conditions.

Modeling lactation curves using mathematical equations helps describe and predict productive behavior in dairy cattle. Additionally, it enables the implementation of nutritional management strategies, simulation of agricultural systems, and prediction of greenhouse gas emissions

(Castillo-Gallegos 2018). Models of varying degrees of complexity have been used to represent lactation curves more accurately (Castillo-Gallegos 2018). Some models with more parameters even incorporate mechanistic elements contributing to the description of curves based on biological references, such as cellular growth and death in the mammary gland (Dijkstra et al. 1997).

Although previous studies have described parameters for lactation curves in small-scale dairy production systems (García-Muñiz et al. 2007; Lemus-Ramírez et al. 2008), no research has been conducted to determine the model with the best fit, leading to uncertainty in predictions. Furthermore, lactation curves have been rarely studied (e.g., Val-Arreola et al. 2004), and the heterogeneity of production units limits the possibility of extrapolating results from studies conducted in different regions.

In the western region of Mexico, the state of Jalisco stands out as having the highest milk production in the country, 60% of which comes from small-scale dairy farms (SIAP 2021). Despite the importance of this state in smallholder milk production, no studies have been conducted to compare the performance and fit of different models in lactation curves in this region. Therefore, this study aimed to evaluate the capacity of different mathematical models to describe lactation curves in dairy cattle within the small-scale dairy system in western Mexico. Our working hypothesis was that at least one equation is useful for describing lactation curves in such system.

Methods

Farm selection, management, and data collection

The study was conducted in the Los Altos region, in the state of Jalisco, western Mexico. The geographical coordinates of the study area are 20°49.017'N, 102°43.983'W, with an elevation of 1800 masl. The climate in this region is temperate and subhumid, with average minimum and maximum temperatures of 4.2 °C and 31.6 °C, respectively. The average annual precipitation is 880.9 mm, and the rainy season extends from June to September.

Since no complete and updated inventory of small-scale dairy farms was available, a convenience sample was selected based on the following criteria: 1) family labor as the primary operational support of the farm, 2) fewer than 100 cows, and 3) a medium-low level of technology (i.e., having few individual milking machines and no refrigeration tanks). Twenty-three farms were included, with an average of 40.7 cows in production (range 24–98). Of the cows in the study, 99% belonged to the Holstein breed. All cows selected for the study were evaluated as healthy through clinical examination. Modifications to farm management during data collection were avoided. The farms met the typical characteristics of smallholder farms in Mexico, as reported in previous studies (Vera et al. 2009; Camacho-Vera et al. 2017; Martínez-González et al. 2017).

The cows were housed in dirt pens with shade and unlimited access to water. Over a period of 18 months, monthly milk weighings were conducted on a total of 936 lactations. Milking sessions were conducted at 05:00 and 17:00 hours, and the recorded average production was 23.1 ± 0.1 kg per day. All collected information is part of the National Dairy Information Bank databases of the National Genetic Improvement Program, funded by federal resources.

The details of nutritional management in the region were described by Villarreal-Rodas et al. (2016). The study identified two management groups: total confinement and partial confinement with grazing in rangelands during the rainy season. Cows in total confinement were offered a complete ration with a lactation diet of 40% forage and 60% grain. Depending on the farm, the forage used was silage (70%) or maize stubble (55%), while the grain was supplied with different commercial concentrates containing an average of 20% crude protein. Cows were fed at 06:00 and 18:00 hours. Cows in partial confinement received a supplement with maize stubble or silage and commercial concentrates when rangeland forage was limited. Deficiencies in nutritional intake have been reported for both groups according to individual productive potential (Martínez-García et al. 2015; Villarreal-Rodas et al. 2016; Gómez-Rosales et al. 2020).

Equations

Five equations previously used by Val-Arreola et al. (2004) in Mexico and Hossein-Zadeh (2019) in Iran were considered for describing lactation curves in this study: those proposed by Gaines (1927), Sikka (1950), Wood (1967), Rook et al. (1993), and Dijkstra et al. (1997). The mathematical models describing the curves and a brief description of each are shown in Table 1. The parameter '*a*' describes the intercept on the ordinate axis (milk production) in a graph

Table 1. Evaluated models used to describe lactation curves in dairy cattle.

Model and description	Equation
Gaines: a two-parameter equation that considers maximum milk production at calving.	$Y = ae^{-bt}$
Sikka: an equation that incorporates an initial increase in the milk production curve.	$Y = ae^{(bt+ct^2)}$
Wood: an equation that accounts for a maximum point of milk production occurring after the start of lactation followed by a gradual decline until drying off.	$Y = at^b e^{-ct}$
Rook et al.: a mechanistic model that incorporates a representation of the lactation curve combining elements of the growth and decline process.	$Y = a\{\frac{1}{[1+\frac{b}{c+t}]}\}e^{-dt}$
Dijkstra et al.: a mechanistic model that takes into account the process of cell proliferation and death in the mammary gland to describe the lactation curve.	$Y = ae^{\left[\frac{b(1-e^{-ct})}{c}-dt\right]}$

Y is the milk production in kg d^{-1}, *t* is the day of lactation, and *a* – *d* are parameters that define each curve.

where the abscissa axis indicates days in milk. The other parameters determine the maximum milk production, the shape, and position of each curve.

Statistical analysis

All analyses were performed using SAS version 9.4 (SAS Institute Inc., Cary, NC). For the lactation number, three categories were considered: cows in their first, second, and third (or higher) lactations. In small-scale dairy farms, providing extra feed (concentrate) to high-producing cows during milking is common, increasing herd variability in production per cow. To control for this effect, animals were categorized according to their production level, and the parameters of each curve were obtained for each group. Cows were classified into three groups based upon quartile distribution of the sample according to the level of milk production standardized to 305 days (Bijttebier et al. 2017). Cows with low, intermediate, and high production levels corresponded to less than 5505 kg (first quartile), 5505–8285 kg, and more than 8285 kg of milk (third quartile), respectively. The calving season effect was controlled by adjusting production according to the calving month (Val-Arreola et al. 2004; Demeter et al. 2011); June was considered the reference month as it had the lowest variation in milk production.

The NLIN procedure was used to obtain preliminary parameters, and the NLMIXED procedure was used to obtain the final parameters of each curve. The farm effect was included as a fixed and random effect (Val-Arreola et al. 2004). The Bayesian information criterion (BIC) and the mean square prediction error (MSPE) were used to compare model performance. The BIC allows the selection of the best model considering the principle of parsimony by penalizing more complex models, while the MSPE measures the average square difference between the values predicted by a model and the observed actual values. Lower values indicate a better fit in both indicators. The root mean square prediction error (RMSPE) and its root as a percentage of the observed mean (%RMSPE) were used to evaluate the accuracy of the models (Val-Arreola et al. 2004). RMSPE measures the discrepancy between the values predicted by a model and the observed values, allowing for an error measure in the original scale. Finally, %RMSPE allows the evaluation of the model's error relative to the range of observed values. Lower RMSPE and %RMSPE values suggest greater model accuracy.

Results and discussion

The study utilized five models previously used to describe dairy cattle lactation curves in small-scale production systems (Val-Arreola et al. 2004; Khan et al. 2012). Table 2 presents descriptive statistics of daily milk production, overall production, and production standardized to 305 days per lactation. Fig. 1 illustrates the fit of each model to the milk production information per lactation (Fig. 1A–C) and per lactation within each production level (Fig. 1D–L).

Table 2. Descriptive statistics of daily milk production and production standardized to 305 d.

Lactation number	Milk production (kg d^{-1})			
	Mean ± SEM	Q1	Median	Q3
1	20.1 ± 0.14	16.0	19.9	24.0
2	23.8 ± 0.22	18.3	23.8	29.5
≥3	24.7 ± 0.16	18.3	24.6	31.1
All	23.1 ± 0.01	17.3	22.4	28.5
	305-d standardized milk production (kg)			
	Mean ± SEM	Q1	Median	Q3
1	6842.7 ± 110.7	5650	6765	7970
2	7080.1 ± 144.7	5650	7180	8440
≥3	6849.8 ± 97.4	5385	6810	8360
All	6894.0 ± 65.5	5505	6910	8285

≥3, cows with three or higher lactations; SEM, Standard error of the mean; Q1, First quartile; Q3, Third quartile.

Parameter estimates and performance indicators of the models are presented in Suppl. material 1. The Dijkstra et al. model did not adequately fit the production data obtained in this study. The other four models fit well with the milk production data and did not present apparent problems describing the lactation curve (Fig. 1). Overall, the Gaines model performed the best for cows in their first, second, or third (or higher) lactations, showing lower BIC and RMSPE values (Table 3). Regarding accuracy, the Gaines and Sikka models had the lowest RMSPE and %RMSPE values (Table 3).

The Gaines model is the simplest as it uses only two parameters and does not consider the existence of a production peak. Instead, it starts from a theoretical initial production at calving and gradually declines until drying off. This pattern has been observed in small-scale dairy production systems (Val-Arreola et al. 2004). However, it is interesting to note that the better performance of the Gaines model in this study contrasts with what has been reported in other works. García-Muñiz et al. (2007) conducted a study in the same region and similar production units, where they evaluated the effect of technological level on milk production and lactation curve characteristics. In their study, the authors found that the Wood model fit their data well. However, they only evaluated one model and did not explore other options that might have performed better. On the other hand, Val-Arreola et al. (2004) reported that Dijkstra et al.'s model was the best fit for the production unit data in the central region of Mexico. One possible explanation for these discrepancies could be that production levels and genetic composition differ in the Los Altos region (García-Ruiz et al. 2015). However, the trend of a continuous decline without a production peak, observed in both this study and that by Val-Arreola et al. (2004), is consistent with our results, indicating a better performance of the Gaines model.

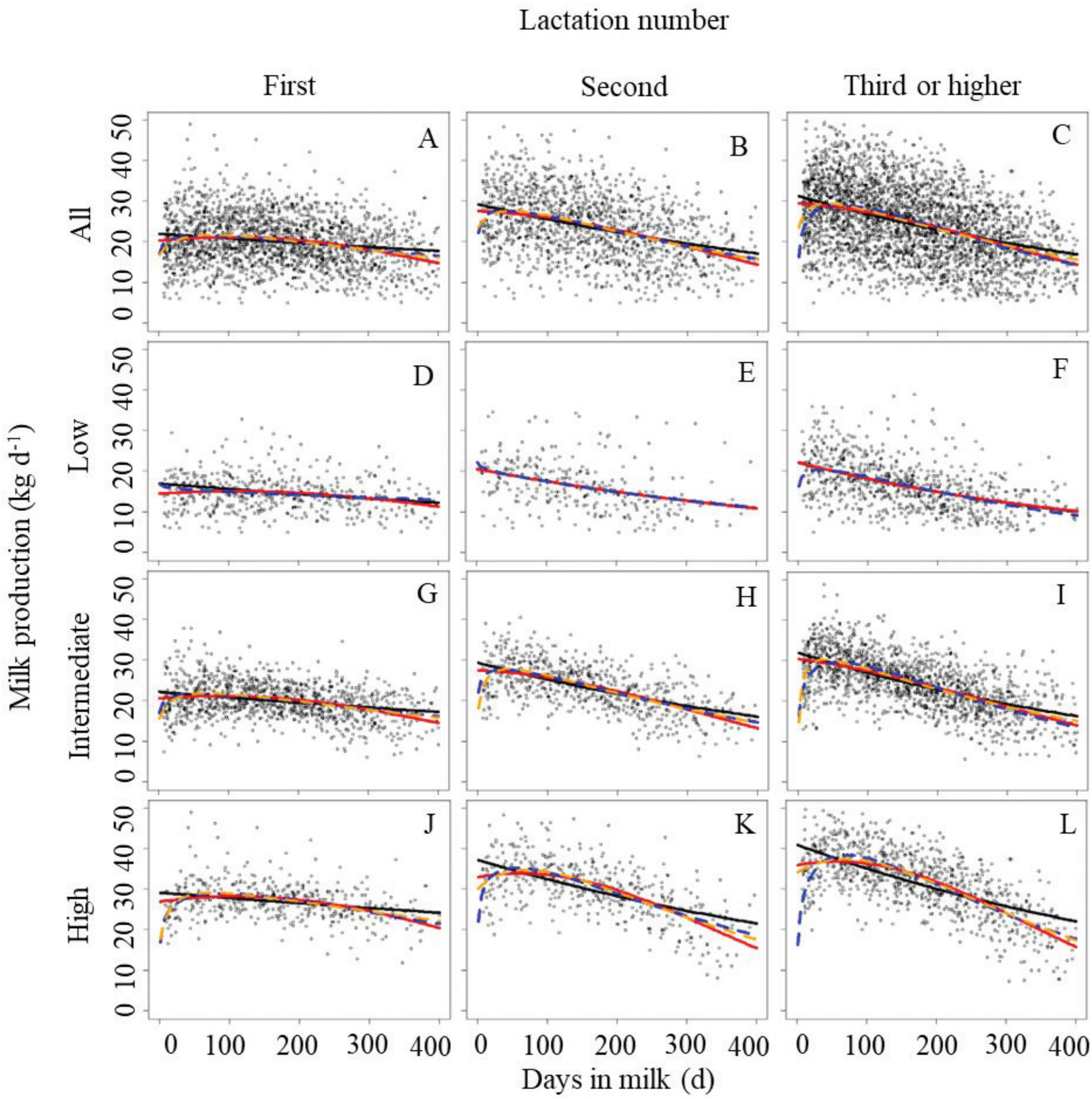

Figure 1. Lactation curves of cows in a small-scale dairy system in Mexico. Circles (O) represent milk production (adjusted values). Lines indicate the fit of the analyzed equations, Gaines (continuous black line), Sikka (continuous red line), Wood (dashed blue line), Rook et al. (dashed orange line). Panels **A**, **B**, and **C** show milk production in all the cows in their first, second, and third (or higher) lactations, respectively. Panels **D**, **E**, and **F** show milk production of cows with low production in their first, second, and third (or higher) lactations, respectively. Panels **G**, **H**, and **I** show milk production of cows with intermediate production in their first, second, and third (or higher) lactations, respectively. Panels **J**, **K**, and **L** show milk production of cows with high production in their first, second, and third (or higher) lactations, respectively.

Small-scale milk production system in Mexico exhibits significant variability (Vera et al. 2009). This variability is attributed to characteristics such as herd size, health status, genetic potential, level of technification, and nutritional management. Moreover, variability was also noted in production levels within each lactation. For instance, in first lactation cows, milk production in the initial 100 days ranged from 6 to 49 kg per day (Fig. 1). Nutritional management is considered one of the primary factors contributing to this variability. It has been reported that nutrition is inadequate in this production system and fails to fully exploit the animals' genetic potential (Martínez-García et al. 2015; Villarreal-Rodas et al. 2016; Gómez Rosales et al. 2020). Additionally, it is common practice to provide extra concentrate to cows with higher milk production during milking, as they are not sorted in pens based on lactation stage or production level.

When examining small-scale milk production systems, a quartile-based classification of production levels has been proposed to facilitate comparisons between extreme values

Table 3. Performance of different models using four metrics for lactation curves of cows in small-scale farms.

Production level classification	Lactation	Model	Performance indicators of the models			
			BIC	MSPE	RMSPE	%RMSPE
All	1	Gaines	21792	3.206	1.779	35.6
		Sikka	21795	3.041	1.704	34
		Wood	21795	3.935	1.985	39.2
		Rook et al.	21798	4.767	2.144	43
	2	Gaines	14662	3.634	1.894	45
		Sikka	14873	3.735	1.894	44.3
		Wood	—	4.369	2.065	49.2
		Rook et al.	—	5.217	2.25	53.8
	≥3	Gaines	33213	2.327	1.516	37.3
		Sikka	33899	2.472	1.542	37.2
		Wood	33216	2.732	1.638	40.4
		Rook et al.	33218	3.044	1.716	42.5
Low	1	Gaines	5301	6.457	2.524	36.3
		Sikka	5304	7.899	2.789	40.2
		Wood	5304	8.181	2.814	40.5
		Rook et al.	—	—	—	—
	2	Gaines	3259	7.758	2.766	45.3
		Sikka	3308	9.996	3.131	51.3
		Wood	3261	9.357	3.014	49.7
		Rook et al.	—	—	—	—
	≥3	Gaines	8307	4.691	2.152	35.9
		Sikka	8481	4.935	2.179	35.3
		Wood	8310	5.94	2.319	38.8
		Rook et al.	—	—	—	—
Intermediate	1	Gaines	12001	4.369	2.076	41.4
		Sikka	12003	4.119	1.985	39.4
		Wood	12003	5.305	2.274	45.9
		Rook et al.	12006	6.181	2.44	48.7
	2	Gaines	6831	5.326	2.293	53.3
		Sikka	6931	5.492	2.299	52.5
		Wood	6834	6.442	2.507	58.4
		Rook et al.	6836	6.88	2.577	60.3
	≥3	Gaines	15691	3.39	1.83	45
		Sikka	16018	3.613	1.866	44.9
		Wood	15694	3.998	1.982	48.9
		Rook et al.	15969	4.267	2.028	50.2
High	1	Gaines	4498	7.119	2.649	71.3
		Sikka	4500	6.7	2.529	68.1
		Wood	4500	8.529	2.887	77.7
		Rook et al.	4503	9.184	2.98	80.2
	2	Gaines	4578	6.462	2.526	75.1
		Sikka	4645	6.742	2.547	78.8
		Wood	4580	7.836	2.767	82.6
		Rook et al.	4583	7.882	2.781	83
	≥3	Gaines	9214	4.38	2.08	66
		Sikka	9406	4.724	2.135	66.6
		Wood	92116	5.185	2.257	71.9
		Rook et al.	9218	4.44	2.093	66.7

BIC, Bayesian information criteria; MSPE, mean square prediction error; RMSPE, root mean square prediction error; %RMSPE, RMSPE as a percentage of the observed mean; ≥3, cows with three or higher lactations; —, not calculated for lack of adjustment to the data.

within the sample (Bijttebier et al. 2017; Montiel-Olguín et al. 2019). Our study adopted this approach, categorizing cows based on their production levels to mitigate observed variability (Fig. 1). This approach was used to explore whether such heterogeneity might restrict improved precision in models other than the Gaines model. Table 4 presents the estimated parameters of the equations that exhibited superior fit and precision in the analyses accounting for production level (Gaines and Sikka). The Rook et al. model did not adequately conform to the milk production data from cows categorized as low producers. The Gaines model emerged as the most effective across cows classified as low, intermediate, and high producers in first, second, and third (or subsequent) lactations, displaying lower BIC and MSPE values (Table 3).

Although the quartile classification based on production level helped control variability in daily milk production values (Fig. 1), the accuracy of the models did not

Table 4. Parameters for Gaines and Sikka models by production level and lactation number in small-scale dairies.

Model	Lact	Parameter	All	Production level†		
				Low	Intermediate	High
Gaines	1	*a*	22	17	22.2	29.2
			(4.67)	(8.95)	(6.58)	(10.75)
		b	0.001	8.22E-04	6.35E-04	4.65E-04
			(0.001)	(0.003)	(0.002)	(0.002)
	2	*a*	29.3	20.6	29.4	37.2
			(5.83)	(12.82)	(8.6)	(10.52)
		b	0.001	0.002	0.002	0.001
			(0.001)	(0.004)	(0.002)	(0.002)
	≥3	*a*	31.3	22.2	32	41
			(3.77)	(7.81)	(5.55)	(7.25)
		b	0.002	0.002	0.002	0.002
			(0.001)	(0.002)	(0.001)	(0.001)
Sikka	1	*a*	20.3	14.5	20.6	27
			(0.000)	(14.31)	(0.000)	(0.68)
		b	8.45E-04	7.68E-04	6.86E-06	8.57E-04
			(0.002)	(0.001)	(0.003)	(0.000)
		c	-4.07E-06	-3.45E-06	-3.87E-06	-3.87E-06
			(0.000)	(0.000)	(0.000)	(0.000)
	2	*a*	27.6	20.6	27.5	33
			(0.000)	(20.07)	(0.000)	(0.000)
		b	-2.30E-04	-0.002	-2.80E-04	8.62E-04
			(0.002)	(0.01)	(0.003)	(0.003)
		c	-3.50E-06	-9.88E-08	-9.89E-06	-6.90E-06
			(0.000)	(0.000)	(0.000)	(0.000)
	≥3	*a*	29.6	22.3	30.5	36
			(0.000)	(0.000)	(0.000)	(0.000)
		b	-4.50E-04	-0.002	-7.30E-04	8.54E-04
			(0.001)	(0.004)	(0.002)	(0.002)
		c	-3.40E-06	2.90E-07	-3.03E-06	-7.28E-06
			(0.000)	(0.000)	(0.000)	(0.000)

Lact, lactation; *a*, *b* and *c* are parameters that define the shape of the curve; ≥3, cows with three or higher lactations. †Standard error of the parameters is indicated within parenthesis.

improve, especially in cows with intermediate or high production levels (higher %RMSPE). Additionally, it is noteworthy that a production peak was observed in high-producing cows in the second and third (or higher) lactations, although it is not fully defined (see Fig. 1 panels K and L). Despite this, the Gaines model performed the best in these classifications. One possible explanation for the inability of other models to detect lactation peaks could be the lack of sufficient observations during the early lactation stage (Khan et al. 2012). Another possibility is that the definition of the lactation peak is not so pronounced as to allow other models designed to describe a more complex production curve to perform better. In other words, the models used in the study may be more suitable for describing a gradual and descending lactation curve rather than pronounced peaks. As for the other categories, the results were expected as a more evident descending slope is observed in lactation curves. This fact explains the better performance obtained with the Gaines model.

The results indicate that multiparous cows exhibit higher average and total production than cows in their first lactation (Table 2). The initial production level and the persistence of the lactation curve can explain these findings. The Gaines model considers maximum milk production at the time of calving, which does not align with lactation physiology. However, this higher initial production (parameter a in the Gaines model) contributes to a higher average production. On the other hand, parameter b of the Gaines model has an inverse relationship with the persistence of the lactation curve. The results indicate that persistence is higher in cows in their first and second lactations, whereas the decline in production is slightly more pronounced in cows in their third or subsequent lactations. Unlike technified systems, there are financial limitations in small-scale milk production systems that may hinder optimal feeding and milk production. One option that could be explored is strategic energy supplementation, aiming to increase initial production in primiparous cows and improve persistence in the lactation curve in multiparous cows. This strategy could help mitigate nutritional and financial limitations present in small-scale milk production systems and potentially enhance the productive performance of cows.

Conclusions

Among the compared equations, the Gaines model emerges as the best option for representing the lactation curve of cows in small-scale milk production system in western Mexico. The superiority of the Gaines model persists even when classifying animals by production level, indicating its ability to capture the characteristics of the lactation curve across different production categories. These results suggest that the Gaines model is robust and suitable for describing the observed variability in cows under this production system.

Competing interest

The authors have declared that no competing interests exist.

Data accessibility

The data can be accessed by contacting the corresponding author at hector.raymundo.vera@uaq.mx, upon reasonable request.

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Supplementary material

Supplementary material 1

Parameters and performance indicators of models adjusted for milk production by lactation number and at different production levels (low, intermediate, and high) in cows from a small-scale dairy system in western Mexico. (.docx file)

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