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CHARACTERIZATION OF THE LACTATION CURVE OF RAMBOUILLET EWES IN MEXICO

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ABSTRACT

Sheep (*Ovis aries* L.) in Mexico are mainly used for meat production, especially for the Mexican dish known as 'barbacoa'. There is a growing interest in genetically improving ewe breeds with a focus on milk production for cheese, which is increasing in demand internationally. Among other things, this highlights the importance of understanding the lactation curve (LC) in ewes. The objectives of the present study were: a) to characterize the LC of Rambouillet ewes using Wood's model ($Y_t = at^b e^{-ct} + \varepsilon_i$), estimating its three parameters (*a*, *b*, *c*) and other measures of interest: lactation peak (LP), lactation peak day (DLP), and lactation persistency (PER); b) assess the effects of the number of lambs (NL), the type of lambing (TL), and the weaning time of the offspring (WT) on Wood's model parameters and those of the LC; and c) estimate phenotypic correlations between Wood's model and the LC parameters. The results showed that the LC obtained was a 'typical' curve with parameters *a* = 901.2 mL, *b* = 0.1206, *c* = -0.01299, LP = 1045.1 mL, DLP = 9.2 d, and PER = 2.1. There were significant effects ($p \leq 0.05$) of WT on *a* and of WT and TL on PER; the highest mean of *a* (957.4) was obtained with weaning at eight weeks. On the other hand, the largest PER averages were found in single lambs and at six of weeks weaning. Phenotypic correlations ($p \leq 0.05$) were estimated between and within Wood's model and the LC parameters. The results of the present study support the recommendation of a milk production system for Rambouillet ewes to make cheese.

Keywords: milk production, mathematical functions, phenotypic correlations, persistence, non-genetic factors.

INTRODUCTION

Sheep are found throughout Mexico, especially in the central-northern region. The 'social sector,' characterized by having fewer than 30 animals, accounts for the greatest percentage of producers (Cuéllar *et al.*, 2012). Currently, sheep farming in the country is focused on the production of meat for the preparation of the traditional dish known as 'barbacoa,' using breeds such as Suffolk, Hampshire, Dorset, Charollais, Texel, Pelibuey, Blackbelly, Katahdin, and others. Due to the introduction of specialized breeds for milk production, such as East Friesian, Awassi, Lacaune, and Assaf, ewe milk production systems in Mexico are relatively new (Ángeles-Hernández *et al*., 2018; Velarde-Guillén *et al*., 2022). Therefore, information related to production indices and lactation characteristics, such as the lactation curve shape, lactation peak, and lactation persistence, is still limited (Ángeles-Hernández *et al*., 2013, 2014). However, there is interest in implementing genetic improvement programs for ewes to increase milk production due to a growing market demand, especially for ewe's milk-based cheeses (Haenlein and Wendorff, 2006).

Mexico was a major producer of sheep wool, but because of the low fiber quality and low prices, wool production is no longer significant. In this sense, the Rambouillet breed had a crucial role in the production of wool at the national level; however, this production system was complicated due to the appearance of synthetic fibers, such as polyester, nylon, and linen. Since breeds like the Dorset, Rambouillet, and Suffolk in the USA have demonstrated good potential for milk production (Sakul and Boylan, 1992), Ochoa-Cordero *et al*. (2002) examined the production and composition of milk from Rambouillet ewes in Mexico in order to find a solution for milking ewes and using the milk to make cheese.

Understanding the lactation curve (LC) in ewes is crucial because it serves as a very significant indicator of milk production, in addition to allowing decisions to be made on aspects such as nutrition, health, and flock management. It is also useful for identifying and selecting ewes that are productively superior (Chang *et al*., 2001). The LC represents the variation of milk production as a function of time and is represented either numerically on a time basis or graphically by postpartum diagrams (Keskin and Dağ, 2006) and is characterized by a mathematical function (Quintero *et al*., 2007). LC studies have been previously carried out in Mexico, mainly in ewes specialized in milk production (Ángeles-Hernández *et al*., 2013, 2018).

Ochoa-Cordero *et al*. (2002) concluded that the quality of milk from Rambouillet ewes suggests its use in cheese and yoghurt production in an attempt to obtain additional income from current production systems with this breed. However, they did not characterize the LC, which contains very important information such as lactation peak (LP, date of maximum milk production), lactation peak day (DLP), and lactation persistency (PER), all of which determine the shape of the LC. Therefore, the objectives of the present study were: 1) to characterize the lactation curve in a population of Rambouillet ewes using the Wood model (1967); 2) to evaluate the effect of non-genetic factors affecting the parameters of this model (a, b, c), LP, DLP, and PER; and 3) to calculate phenotypic correlations between Wood's model parameters, LP, DLP, and PER.

MATERIALS AND METHODS

Animals and management

The study was conducted using the milk production records of 45 Rambouillet ewes with one to three lambings, one or two offspring, and an average live weight of 65±7.1 kg. The animals belonged to the sheep flock of the Faculty of Agronomy of the Autonomous University of San Luis Potosí. At an altitude of 1835 m, the climate at the site is cold and dry, with an average temperature of 17.8 °C and annual rainfall of 271 mm (García, 2004).

Ewes were confined and fed daily 3.5 kg of fresh alfalfa (*Medicago sativa* L.) and 1.7 kg of a commercial feed with 14 % crude protein and 2.96 Mcal kg^{-1} of digestible energy. The same diet was offered to the ewes in the morning (8:00) and the afternoon (13:00). Ewes were divided into two groups based on whether their offspring were weaned at six or eight weeks of age. Hand milking was done twice a day (8:00 and 13:00) beginning the first week postpartum, with no stimulus to allow milk let-down. During the lactation period, ewes were milked every seven days, with offspring separated from dams at 16:00 on the day before milking. After milking, the lambs were returned to their mothers. Further details on management are given in Ochoa-Cordero *et al*. (2002).

Statistical analysis

Characterization of the lactation curve

Individual ewe lactation averages were captured in a spreadsheet. Weekly milk production data were adjusted using the Wood model (1967):

$$Y_t = at^b e^{-ct} + \varepsilon_i$$

where Y_t is the milk yield obtained on day t; a is a scaling factor or milk yield at the start of lactation; b is the slope of the curve in the rising phase; e is the natural logarithm; c is the slope of the curve in the falling phase; and ε_i is the random error. Although it overestimates milk production at the beginning of lactation and underestimates it near and after the LP (Dematawewa *et al*., 2007; Dijkstra *et al*., 2010), it is still the most widely used model to model lactation curves in ewes (Pollott and Gootwine, 2000; Nezamidoust *et al*., 2013; Ángeles-Hernández *et al*., 2013).

Following a logarithmic transformation, the model was analyzed linearly as follows:

$$Y_t = ln\ a + b\ ln\ t - ct$$

Subsequently, the parameters *a*, *b*, and *c* were estimated by multiple linear regression. According to Nezamidoust *et al*. (2013) and taking the averages of all ewes, the lactation peak (LP) was estimated as $a\ (b/c)^b\ \ e^{-b}$, while the lactation peak day (DLP) was calculated as b/c.

Wood's model parameter estimation

In addition, the persistency of lactation (PER), which is a phase of lactation that indicates the ability of an ewe, cow, or goat to continue producing milk after reaching peak production, was included in the statistical analysis (Swalve and Gengler, 1999; Cobuci *et al*., 2003). The PER was estimated using the Wood method (1968) as follows:

$$PER = -\ (b + 1)\ ln\ c$$

With this model, PER values are expressed without units of measurement. However, it is understood using a specific regression coefficient (Madsen, 1975), percentages (Sölkner and Fucks, 1987), proportions based on milk production during a specific lactation period in relation to a previous one (Sölkner and Fucks, 1987), random regression genetic coefficients based on a random regression model (Cobuci *et al*., 2007), or grams per day associated with a rate of decline in milk production during the LC decline (Rojo-Rubio, 2016). In addition, lactation curves were also estimated according to the effects of the number of lambs (NL), the type of lambing (TL), and the weaning time of the offspring (WT).

Analysis of variance for non-genetic effects on total parameters

To evaluate the effect of non-genetic factors on Wood's model parameters (*a*, *b*, *c*) and lactation curve parameters (LP, DLP, PER), the following fixed effects model was used:

$$Y_{ijklmno} = \mu + NL_i + TL_j + WT_k + LP_l + DLP_m + PER_n + \varepsilon_{ijklmno}$$

where $Y_{ijklmno}$ = *a*, *b*, *c*, LP, DLP, PER; μ is the overall mean; NL_i is the effect of the *i*-th number of lambs (*i* = 1 to 3); TL_j is the effect of the *j*-th type of lambing (*j* = single, double); WT_k is the effect of the *k*-th weaning time (*k* = 6 or 8 weeks); LP_l is the effect of the *l*-th lactation peak (*l* = 1 to 45); DLP_m is the effect of the *m*-th day of lactation peak (m = 1 to 45); *PERn* is the effect of n-th persistence (n = 1 to 45); and $\varepsilon_{ijklmno}$ = random error ~ NID (0, σ_e). Double interactions between these variables were initially tested, but none showed statistical significance ($p > 0.05$) and do not appear in the final model. Finally, a Pearson correlation analysis was carried out between the parameters of the Wood's model (*a*, *b*, *c*) and those of the lactation curve (LP, DLP, PER). All analyses were carried out using R-Studio software (R Core Team, 2020).

RESULTS AND DISCUSSION

Characterization of the lactation curve

After fitting the ewe milk production data, the LC was obtained (Figure 1), where the average values of the Wood's model parameters were a = 901.2 mL, b = 0.1206, and c = -0.01299, with R^2 = 0.66. On the other hand, LP, DLP, and PER values were 1045.1 mL, 9.2 d, and 2.1, respectively.

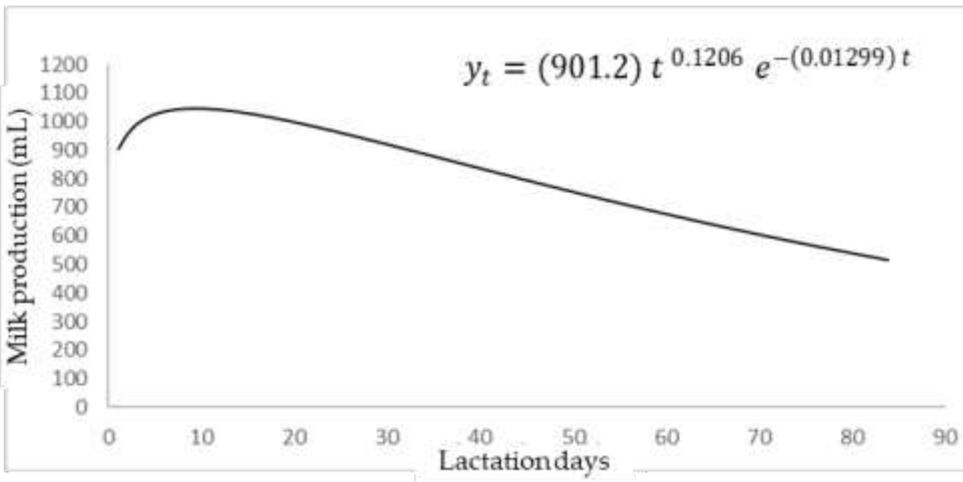

Figure 1. Lactation curve of Rambouillet ewes (*Ovis aries* L.) fitted with the Wood model (1967).

The LC obtained was a typical curve (Ángeles-Hernández *et al*., 2021) as found in non-dairy ewes, including Merino (Groenewald *et al*., 1996), Makui (Nezamidoust *et al*., 2013), Pelibuey (Rodríguez-Álvarez *et al*., 2021), and St. Croix (Merchant *et al*., 2021) breeds. Atypical LCs, which are caused by nutrition, animal health, and environmental disturbances, are also reported in the literature (Macciotta *et al*., 2008). These have been found in F_1 ewes, daughters of Dorset sire and Rambouillet dam (Sakul and Boylan, 1992), and Rambouillet, Suffolk, and Dorset F_1 ewes, daughters of Suffolk sire (Cardellino and Benson, 2002).

In relation to the parameters of Wood's model, it is important to understand the meaning of the combination of signs in parameters b and c, as this provides a clear understanding in relation to the shape of the LC. According to Macciotta *et al*. (2005), when there is a combination of $b > 0$ and $c < 0$, a typical curve is obtained; the combination $b < 0$ and $c > 0$ provides a reverse shape, characterized by an initial phase of decrease to a minimum, followed by an increase; the combination of $b > 0$ and $c > 0$ represents a continuously increasing curve, while the combination $b < 0$ and $c < 0$ represents a continuously decreasing curve.

The literature reports wide variation in mean LP and DLP in ewes. Sakul and Boylan (1992) found LP = 1200 mL and DLP = 14 d in F_1 non-dairy ewes using Wood's model; Groenewald *et al*. (1995) a LP = 1828 mL and DLP = 19 d in Merino ewes using Morant's model; Pollott and Gootwine (2000) a LP = 3.31 L and DLP = 25 d in dairy Awassi ewes using the multiplicative model proposed by Pollot; Dağ *et al*. (2005) a LP = 930 mL and DLP = 60 d in dairy Awassi ewes using the quadratic model; Dağ *et al*. (2005) a LP = 1620 mL and DLP = 10 d in dairy Awassi ewes using the inverse polynomial model; Ángeles-Hernández *et al*. (2013) a LP = 650 mL and DLP = 37 d in F_1 dairy ewes using Wood's model; Miguel *et al*. (2016) a LP = 1337 mL and DLP = 26 d in Ojalada dairy ewes using the Wilmink model; and Velarde-Guillén *et al*. (2022) a LP = 1.2 kg and DLP = 42 d in F_1 dairy ewes using random regression models with orthogonal polynomials of fifth order.

As for PER, information is limited in ewes. The average PER obtained in the present study was 2.1, which could be interpreted as a moderate persistence. This value is lower than that reported by Torres-Hernández and Hohenboken (1980) in F_1 Hampshire crossbred ewes, which was 5.1 using Wood's model. In lambing, Dairymeade ewes from New Zealand, Marshall *et al*. (2023) estimated PER using a different methodology, where the first lambing ewes had PER = 61.5 %, a value higher ($p \leq 0.05$) than the second (53.7 %), third (54.5 %), and fourth (54.2 %) lambing ewes. Akpa *et al*. (2001), with Red Sokoto goats from Nigeria, found a PER (defined as: $c^{-(b+1)}$) equal to 143.2. In Ecuador, Pesántez *et al*. (2014) found a PER = 69.4 % in F_1 Anglo-Nubian x Criollo goats, a value higher than that obtained by Méndez *et al*. (2019) with Alpine goats from Ecuador, which was 53.6 %. Rojo-Rubio *et al*. (2016) used averages of the rate of decline in milk production during the LC decline phase, obtaining PER averages of 10.7, 8.8, and 14.4 g d^{-1} in Alpine, Nubian, and Saanen goats, respectively, with the Alpine and Nubian averages being different ($p \leq 0.05$) from the Saanen average.

Differences in LC shape, LP, DLP, and PER values, in addition to ewe genotype, model used to perform the curve fitting, and sample size used, are also subject to the effect of non-genetic factors known to influence milk production, such as milk production time (Carta *et al.*, 1995), milk production level and type of lambing (Cappio-Borlino *et al.*, 1995), number of lambs (Cappio-Borlino *et al*., 1997a), herd and feeding (Cappio-Borlino *et al*., 1997b), production year and lactation length (Méndez *et al*., 2019; Marshall *et al*., 2023); and climatic factors such as temperature, humidity, wind speed, and radiation (Silanikove, 2000; Naskar *et al*., 2012).

Non-genetic effects on parameters

The number of lambs (NL), the type of lambing (TL), and the weaning time (WT) showed significant effects ($p \leq 0.05$) on parameters *a*, *b*, *c*, LP, DLP, and PER (Table 1). WT had an impact on *a*, while TL and WT had an effect on PER. The highest average value for *a*, according to WT, was at eight weeks of weaning (Table 2). The fact that parameter ***a*** had no effect (***p*** > 0.05) on single and double lambing ewes could be attributed to the number of offspring suckling that explains milk production, not the

Table 1. Summary of the analysis of variance with mean squares for the test of parameters according to the effects of the number of lambs (NL), the type of lambing (TL), and the weaning time of the offspring (WT) of Rambouillet ewes (*Ovis aries* L.).

	df	*a*	*b*	*c*	LP	DLP	PER
NL	2	54 554.3	0.011	0.000	81 409.5	276.9	0.017
TL	1	24 738.5	0.002	0.003	9820.5	2.04	0.248*
WT	1	203 700.7*	0.000	0.002	138 343.9	669.8	0.334*

df: degrees of freedom; *a:* milk yield at the start of lactation; *b*: slope of the curve in the rising phase; *c*: slope of the curve in the falling phase; LP: lactation peak; DLP: lactation peak day; PER: lactation persistency. *$p \leq 0.05$.

Table 2. Least-squares means of the parameters evaluated according to effects of the number of lambs (NL), the type of lambing (TL), and the weaning time of the offspring (WT) of Rambouillet ewes (*Ovis aries* L.).

	Effect	n	*a*	*b*	*c*	PL	DPL	PER
NL	1	18	897.2±63.6	0.102±0.03	0.011±0.002	1021.2±59.7	17.1±7.9	2.18±0.05
	2	11	955.7±59.2	0.151±0.02	0.016±0.001	1148.8±32.1	9.2±1.2	2.09±0.04
	3	16	847.3±46.9	0.138±0.03	0.026±0.013	1039.5±67.3	9.7±2.2	2.03±0.10
TL	Single	24	888.9±39.1	0.126±.0.02	0.013±0.001	1065.2±34.4	13.2±4.2	2.15±0.03a
	Double	21	910.7±67.6	0.129±0.05	0.034±0.021	1043.8±95.7	10.3±1.8	1.94±0.16b
WT	6 weeks	35	838.0±49.2b	0.128±0.02	0.012±0.001	1011.1±56.0	5.9±5.9	2.19±0.04a
	8 weeks	10	957.4±41.7a	0.126±0.02	0.024±0.010	1116.7±34.3	8.6±1.8	2.02±0.07b

n: sample size; *a:* milk yield at the start of lactation; *b*: slope of the curve in the rising phase; *c*: slope of the curve in the falling phase; LP: lactation peak; DLP: lactation peak day; PER: lactation persistency. Different literals between rows and within variables indicate statistical significance ($p \leq 0.05$).

number of offspring born (Peart, 1967; Corbett, 1968). However, milk production in ewes is known to be higher in the case of double lambings (Figure 2) (Abecia and Palacios, 2017; Rosales-Nieto et al., 2018).

In Yankasa ewes, Afolayan *et al*. (2002) found an effect of the type of lambing ($p \leq 0.05$) on parameters *b* and *c*, where the highest averages were found for single lambing ewes. Significant effects ($p \leq 0.05$) of other non-genetic effects on *a*, *b*, and *c*, such as the age at lambing (Carta *et al*., 1995), milk production level, udder health (Cappio-Borlino *et al*., 1997a), flock, year, and month of lambing (Ruiz *et al*., 2000), milking method (Nezamidoust *et al*., 2013), and lambing time (Ángeles-Hernández *et al*., 2013), have also been found in other ewe breeds.

For the PER variable, the highest average in TL was obtained for single lambs. This result is consistent with the findings of Ruiz *et al*. (2000) in Latxa ewes. Furthermore, the highest average in WT was found in the six-week weaning (Table 2). Afolayan *et*

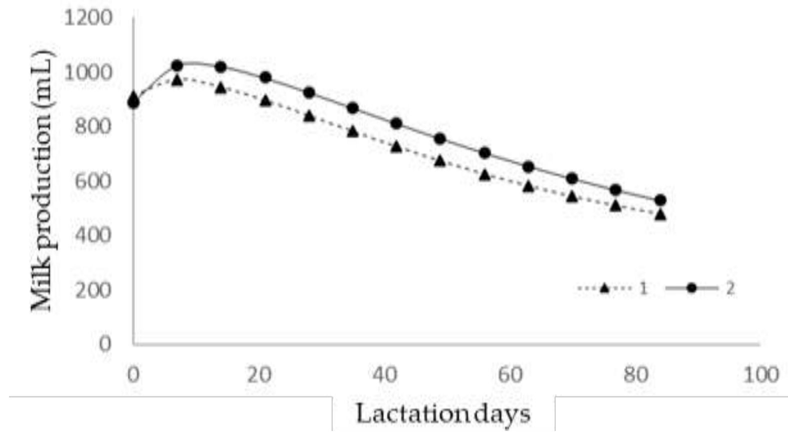

Figure 2. Lactation curve of Rambouillet ewes (*Ovis aries* L.) according to the type of lambing. 1: single lambing; 2: double lambing.

al. (2002) found that parameters *a*, *b*, and *c*, in addition to PER, were affected ($p \leq 0.05$) by the lactation length (84 days of lactation against less than 84 days), finding that the highest averages were in *a* and PER for the 84-day lactation, while the lowest values were found for *b* and *c*. The result for parameter *a* coincides with the present study but is opposite for PER (Figure 3).

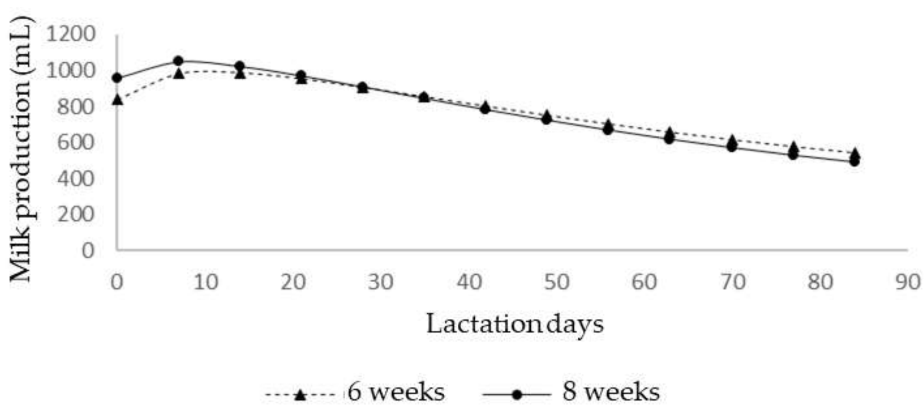

Figure 3. Lactation curve of Rambouillet ewes (*Ovis aries* L.) according to the weaning time of the offspring (six and eight weeks).

Correlation analysis

The correlation *a-b* = -0.38 ($p \leq 0.05$) indicates that curves showing high milk production at the beginning of lactation have a slow growth rate in the slope to reach LP (Table 3). On the other hand, the correlation *b-c* = 0.31 ($p \leq 0.05$) indicates that curves with a

Table 3. Matrix of phenotypic correlations between Wood's model parameters (*a*, *b*, *c*) and lactation curve parameters (LP, DLP, PER).

Parameter	*a*	*b*	*c*	LP	DLP	PER
a	1.00	-0.38**	0.17ns	0.54**	-0.30*	-0.45**
b		1.00	0.31*	0.42**	-0.01ns	-0.04ns
c			1.00	0.08ns	-0.13ns	-0.82**
LP				1.00	-0.42**	-0.12ns
DLP					1.00	0.33*
PER						1.00

a: milk yield at the start of lactation; *b*: slope of the curve in the rising phase; *c*: slope of the curve in the falling phase; LP: lactation peak; DLP: lactation peak day; PER: lactation persistency. *$p \leq 0.05$, **$p \leq 0.01$; ns: not significant ($p > 0.05$).

high growth rate in slope during their ascent to the LP have a moderate rate of decline in slope after reaching the LP. The correlation between parameters *a* and *c* was not significant ($p > 0.05$).

The correlations *a*-*b* and *b*-*c* of the present study are in agreement with the results of Ángeles-Hernández *et al*. (2013, 2014) using dairy ewes in an organic production system in Mexico. However, the result regarding non-correlation *a*-*c* = 0.17 ($p > 0.05$) of the present study differs from these same authors, since they obtained values of -0.36 and -0.41 ($p \leq 0.01$), which means that ewes selected for high milk production at the beginning of lactation have a high PER in milk production. However, Ruiz *et al.* (2000) obtained a correlation of 0.46 ($p \leq 0.01$) between *a* and *c* in Latxa dairy ewes, which indicates the opposite of a negative correlation between both parameters, i.e., ewes with a high production at the start of lactation show a low PER in milk production.

It is possible that the lack of statistical significance of the correlation between *a* and *c* in this study is due to the sample size used. Non-significant correlations ($p > 0.05$) between parameters *a* and *c* were also reported by Groenewald *et al.* (1995) in Merino ewes and by Chang *et al*. (2001) in dairy ewe flocks crossed with meat and wool ewes.

No results of comparable correlations in ewes between Wood's model parameters (*a*, *b*, *c*) and LC parameters (LP, DLP, PER) were found in the literature. Waheed and Khan (2013) obtained correlations *a*-PL = 0.87 and *a*-DPL = -0.85 ($p \leq 0.01$) in Beetal goats, indicating that curves with high milk production at early lactation reach a large LP at an early date. These are similar results to those obtained by Shaat (2014) in Zaraibi goats from Egypt, with significant correlations *a*-LP = 0.97 and *a*-DLP = -0.56 ($p \leq 0.05$). In the study with Zaraibi goats (Shaat, 2014), correlations *b*-DLP = 0.35 and *b*-PER = -0.33 ($p \leq 0.05$) were also found, indicating that curves with a high growth rate during the upward slope reach the LP at an early date but have a low PER. In another study with local goats in Tunisia, Atoui *et al.* (2024) also obtained a correlation *b*-LP = 0.6 ($p \leq 0.05$), indicating that curves with a high growth rate in their slope during ascent have a large LP.

Regarding correlations between LC parameters, the LP-DLP = -0.42 ($p \leq 0.01$) correlation means that, on average, curves with a larger LP take less time to reach it. This result is in agreement with Velarde-Guillén *et al*. (2022) in F_1 dairy ewes (mainly ½ Assaf, ½ Awassi, ½ East Friesian, and ½ Lacaune) from Mexico and Shaat (2014) in Zaraibi goats from Egypt, with values of -0.27 and -0.33 ($p \leq 0.05$), respectively. However, it differs from the result obtained by Atoui *et al*. (2024), who reported a correlation of 0.86 ($p \leq 0.01$) between these same parameters. The DLP-PER = 0.33 ($p \leq 0.05$) correlation indicates that curves with a larger PER take longer to reach the LP. This is consistent with the results obtained by Portolano *et al*. (1997) in Comisana ewes from Italy, Shaat (2014) in goats, and Atoui *et al*. (2024) in goats, who found values of 0.88, 0.58, and 0.57 ($p \leq 0.01$), respectively.

CONCLUSIONS

The use of Wood's model allowed the characterization of the lactation curve of Rambouillet ewes, resulting in a typical curve that has an average initial milk production of 901.2 mL and a lactation peak of 1045.1 mL, which is reached 9.2 days into lactation, and a lactation persistency of 2.1, which can be interpreted as moderate. Parameter *a* (milk yield at the start of lactation) of Wood's model was affected ($p \leq 0.01$) by the weaning time of offspring, while the type of lambing and the weaning time of offspring influenced ($p \leq 0.05$) variation in lactation persistency.

Phenotypic correlations ($p \leq 0.05$) were estimated within and between the parameters of Wood's model and the lactation curve, providing information that provides insight into peculiar aspects of the lactation curve itself and may be useful for general flock management. Although more research is needed on this subject, and given the high quality of the milk from these ewes, these findings are encouraging enough to recommend a milk production system aimed at cheese production in Rambouillet ewes in Mexico, allowing producers to have another remunerative option, as they cannot economically survive with the current wool production system.

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