Tropical Animal Health and Production (2022) 54:192
https://doi.org/10.1007/s11250-022-03144-4

REGULAR ARTICLES

Comparison of models for lactation curves of Holstein, Brown Swiss, and F1 crossbred cows under subtropical conditions

Julio A. Hernández-Zamudio[1] · José A. Villagómez-Cortés[1] · Vicente E. Vega-Murillo[1] · Otto R. Leyva-Ovalle[2] · Jorge G. Vicente-Martínez[1] · Ángel Ríos-Utrera[3]

Received: 15 January 2021 / Accepted: 14 March 2022

Abstract
Tropical and subtropical milk production herds in Mexico generally generate different types of milk-yield records as milk yield per month and mean production per month. Lactation curves generated by these types of records may contribute to understand milk production in the tropical regions of Mexico. The aim of this study was to compare five lactation-curve models fitted to two types of milk-yield records of Holstein, Brown Swiss, and F1 crossbred cows under subtropical conditions. The two types of records ($n = 3756$) used were: (1) milk yield per month (TR) and 2) mean production per months (MR). Goodness-of-fit statistics, including Akaike's information criterion (AIC) and root mean square error (RMSE), were applied to compare the models for each type of records. The Brody model provided the best goodness-of-fit when using monthly milk-yield records, while the Wilmink model provided the best goodness-of-fit for lactation milk-yield records. The RMSE and AIC values were similar between datasets. The final third of the lactation curve showed a little difference between model predictions in both datasets. The comparison of several models was useful to better describe the actual lactation curves of the herd. The Wood model may be adequate to compare information as a reference with other models for decision making process at milk production.

Keywords Brown Swiss · Holstein · Lactation-curve models · Reciprocal crosses · Tropics

Introduction

Milk-yield data collection is important to determine farm profitability, where recording constancy and accuracy of data are crucial to correctly evaluate herd's milk yield (Migose et al., 2020). Incomplete lactation datasets may lead to inadequate decision making in food efficiency evaluation, individual or collective milk-yield evaluation, and genetic selection of animals (Melzer et al., 2017). Lactation-curve models are widely used to predict and/or compare milk yield at different environmental conditions and lactation stages, for purposes like animal selection and nutritional efficiency evaluation. Model accuracy to describe data depends on records quantity and quality and has proved its usefulness to compare different components of milk, milk-yield differences through seasons, and for different breed lactation performance (Soysal et al., 2015).

Several linear and non-linear mathematical models have been proposed to describe lactation curves. They can be applied to records of a cow or a group of cows for the whole lactation period (Wood, 1967; Pollott and Gootwine, 2000). The models can estimate milk yield through a series of algebraic functions that assume milk yield over time within a standard curve with minimal error. This allows to separate the continuous influence of the environment to obtain a yield resume in time that reflects changes in the environment related to the region, quality of food, and handling system (Macciotta et al., 2005).

In this context, it is important to consider that tropical and subtropical milk yield have differences regarding temperate regions (Meseret et al., 2018). In the tropics, the use of adapted animals and(or) crossbreeds is necessary to withstand environmental adversities such as high temperature

✉ Vicente E. Vega-Murillo
vvega@uv.mx

1 Facultad de Medicina Veterinaria Y Zootecnia, Universidad Veracruzana, Veracruz, Mexico

2 Facultad de Ciencias Biológicas y Agropecuarias, Universidad Veracruzana, Cordoba, Veracruz, Mexico

3 "La Posta" Research Station, INIFAP, Veracruz, Mexico

Published online: 31 May 2022

and low quality and quantity of food. The cross of *Bos taurus* and *Bos indicus* generates animals capable of living in tropical conditions with a profitable production, but these animals do not show the same lactation-curve shape and have shorter lactation length (Němečková et al., 2015). Environmental and breed dissimilarities have an impact on maximum milk production; when such differences exist, the application of lactation-curve models determines regional and cross-breed differences on the sub-tropical regions (Pereira et al., 2016). Lactation curves are generally adjusted to 305 days worldwide, nonetheless, in tropical and subtropical milk production systems shorter lactations have been observed (Janković et al., 2016). In addition, in these systems, farmers do not necessarily register milk yield. At best, they register monthly milk yield of cows. Selection of the appropriate lactation-curve model may depend on the type of records, so it is recommended to run different models for different datasets (Glória et al., 2012). Unfortunately, most small-scale operations in the tropical regions of Mexico misuse lactation-curve models or do not use them at all for milk-yield evaluation or animal selection. The aim of this study was to compare five lactation-curve models and identify the best model for total yield per month (TR) and for the mean yield per month (MR) data sets in Holstein and Brown Swiss cows and their reciprocal crosses under subtropical conditions of Mexico.

Material and methods

Location

This study was carried out at "Las Margaritas" experimental site of the National Institute for Forestry, Agricultural and Livestock Research, located in Hueytamalco, Puebla, Mexico, at 450 m above sea level. The climate is classified as subtropical humid. Average annual temperature is 20.8 °C, the minimum temperature is 15.3 °C in winter, and the maximum temperature is 24.2 °C in summer. The region is characterized by abundant rainfall from July to October and a low temperature period with drizzle from November to the end of February. From March to June, high temperatures combined with low humidity and solar radiation generate stressful conditions.

Data

Information on 320 lactations of Holstein ($n=110$), Brown Swiss ($n=132$), F1 Holstein × Brown Swiss ($n=36$), and F1 Brown Swiss × Holstein ($n=42$) cows were available. Cows were produced through artificial insemination or natural mating from 106 sires and 153 dams. Lactations occurred from 1998 to 2014, with 3657 monthly records available for two datasets: total records TR, with the monthly milk-yield total; and mean records MR, with the mean milk yield for each month, distributed in three to six or more complete lactations. Descriptive statistics for milk yield in general is presented in Table 1.

Cows were maintained in a rotational grazing system on African Star grass (*Cynodon plectostachyus*). Grazing and non-grazing periods for each pasture (1–2 ha. each) lasted 2–3 and 35–40 days, respectively, depending on the season of the year. Each cow received 20–30 kg of fresh, chopped Japanese cane (*Saccharum sinense)* per day, during the cold season. Also, each lactating cow received 1.75 kg of a commercial supplement (16% crude protein) per milking (twice a day), and non-lactating cows received 2 kg of the same supplement.

Lactation-curve models

To describe lactation curves, five models were applied to both datasets, to fit the lactation curve of monthly totals and monthly mean records. These models contemplate the milk yield at a determined time, via the interaction between the initial yield, the yield difference between the start and the lactation peak, and the rate of decrease to the end of lactation that determines milk persistency. The five non-linear models were:

1. Wood's equation

$$Y_t = at^b e^{-ct}$$

2. Wilmink function

$$Y_t = a + be^{-kt} + ct$$

3. Brody's equation

Table 1 Milk yield kg ± standard deviation kg for milk-yield records adjusted to 305 days for Holstein, Brown Swiss, and F1 reciprocal crosses in subtropical conditions

Parity	Ho × BS	BS × Ho	Holstein	Brown Swiss
3	3285.98 ± 666.78	3466.75 ± 926.35	3261.18 ± 638.58	2793.45 ± 604.62
4	4477.41 ± 1111.64	4171.75 ± 1003.30	3599.77 ± 645.01	2891.86 ± 811.22
5	4509.62 ± 976.55	3936.08 ± 801.09	3630.01 ± 800.88	3062.63 ± 787.70
6 or more	3042.43 ± 985.38	3277.21 ± 920.14	2787.70 ± 675.29	3005.78 ± 634.40

$$Y_t = ae^{-bt} - ae^{-ct}$$

4. Cobby's equation

$$Y_t = a - bt - ae^{-ct}$$

5. Sikka model

$$Y_t = a\exp\left(bt - ct^{-2}\right)$$

where Y_t = is the predicted yield in the time t; a, b, and c are the parameters estimated for each model; k was fixed to 0.05 in this study.

Each model was fitted with the NLIN procedure of SAS (2013). The goodness-of-fit of each model was evaluated with the root mean square error (RMSE) and the Akaike's information criterion (AIC), so the best model was the one with the lowest values in both tests. The formulas of these tests were:

1. RMSE = root (RSS / ($n-p-1'$)
2. AIC = $-n \times \ln$ RSS + 2p

where, RSS is the residual sum of squares obtained in each model, ln is the base of the natural logarithm, p is the number of parameters included in the model, and n is the number milk-yield records (Akaike, 1998).

Results

Mean yield per month records

Curve parameter estimates that define the scale and shape of the lactation curve and goodness-of-fit measures of the models fitted to the MR dataset are shown in Table 2. The Brody model (Brody et al., 1924) presented the best goodness-of-fit for the MR dataset, with lowest AIC and RMSE values (10,604.52 and 4.11, respectively). The Cobby model (Cobby and Le Du's, 1978) was the next best fit model, with values of 10,621.80 and 4.11 for AIC and RMSE, respectively. In contrast, the Sikka model (Sikka, 1950) was the worst, considering the AIC and RMSE values. All estimates for the models were significant.

In general, the goodness-of-fit statistics for the Wilmink (Wilmink, 1987) and Cobby models were similar. The Wood model was close to the Brody, Cobby, and Wilmink models according to the minimum AIC and RMSE value, making these four models viable to describe the lactation of crossbreed cows under subtropical conditions.

Monthly mean model goodness-of-fit values and the residual sum of the squares indicate that the tested models may adjust generally well to the transformed mean data from the milk-yield monthly totals.

Results concerning the predictions of the models and the shape of the lactation curve are similar in each test for MR dataset and could be caused by the central trend of the records mean for each model, as shown in Fig. 1. It is noticeable that all the models seem to predict similar values in the latest third of lactation that seem to be the same at the end. The Sikka model failed to predict the first third of lactation.

The MR prediction curve shape represents similarities within models, with the particularity that the Sikka's model does not seem to reach a peak but a declining curve instead. All models seem to underestimate the actual mean milk-yield value at the peak of lactation. The Brody's model prediction was the closest to the actual peak value.

Total yield per month records

The parameter estimates calculated for monthly total milk-yield dataset are presented in Table 3. In general, TR values adjusted better to the Wilmink model, which as mentioned, has a constant k value that was set to 0.05 in this study and is related to the time for reaching the peak. The Wilmink model was the best fitted with an AIC value

Table 2 Curve parameter estimates and goodness-of-fit of five lactation-curve models adjusted to mean yield per month records of Holstein, Brown Swiss, and F1 reciprocal crosses in subtropical conditions

Estimate	Wilmink	Cobby	Wood	Brody	Sikka
a	16.70 ± 0.20	16.568 ± 0.218	4.971 ± 0.52	18.903 ± 0.410	13.690 ± 0.282
b	− 14.30 ± 1.38	0.0311 ± 0.0009	0.3242 ± 0.027	0.0031 ± 0.0001	0.0003 ± 0.001
c	− 0.0316 ± 0.0009	0.0571 ± 0.0033	0.005 ± 0.0003	0.046 ± 0.003	8.15E − 06 ± 0.00001
Goodness-of-fit					
RSS	56,485.20	56,431.80	56,597.20	56,172.80	57,586.20
RSD	3.88	3.87	3.88	3.87	3.92
AIC	10,624.26	10,621.80	10,632.78	10,604.52	10,697.86
RMSE	4.14	4.11	4.18	4.11	4.16

RSS residual sum of squares, *RSD* residual standard deviation, *RMSE* root mean square error, *AIC* Akaike's information criterion

± Estimate standard error

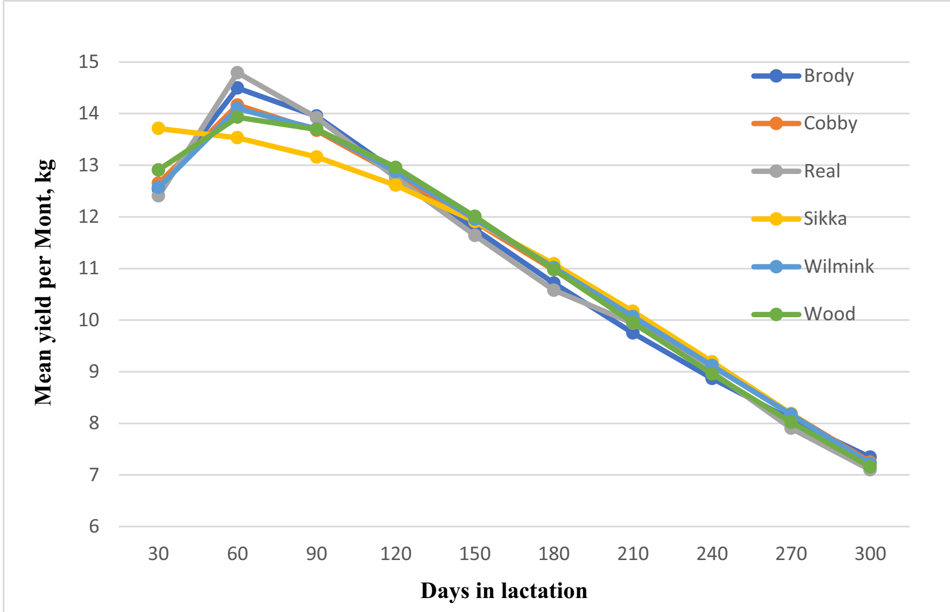

Fig. 1 Lactation-curve model comparison for mean yield per month records of Holstein and Brown Swiss and reciprocal crosses under subtropical conditions

Table 3 Curve parameter estimates and goodness-of-fit of five lactation-curve models adjusted to total yield per month records of Holstein, Brown Swiss, and F1 reciprocal crosses in subtropical conditions

Parameter	Wilmink	Wood	Cobby	Brody	Sikka
a	538.8 ± 5.22	24.78 ± 2.68	557.3 ± 8.55	818.3 ± 42.716	293 ± 6.43
b	− 1112 ± 35.35	0.79 ± 0.02	1.228 ± 0.035	0.00483 ± 0.001	0.004 ± 0.0003
c	− 1.1645 ± 0.024	0.008 ± 0.0001	0.029 ± 0.001	0.0221 ± 0.001	0.0001 ± 0.00001
Goodness-of-fit					
RSS	36,980,735	38,566,840	38,206,258	38,131,126	41,758,747
RSD	99.26	101.37	100.89	100.79	105.48
AIC	34,972.07	35,133.42	35,098.14	35,090.74	35,432.14
RMSE	105.16	107.39	106.88	106.78	111.74

RSS residual sum of squares, *RSD* residual standard deviation. *RMSE* root mean square error, *AIC* Akaike information criteria

± Estimate standard error

of 34,972.07 and an RMSE value of 105.16. The Wilmink model was the second-best model and the Sikka model was the worst fitted in this dataset. Nonetheless, the models' goodness-of-fit values were very similar.

In the TR dataset, estimates for the Wilmink model were $a = 538.8$; $b = -1112$; $c = -1.164$. The curve fits generally better than the other models according to the goodness-of-fit test. In this model, as in some of the other models, the estimate of b is related to the slope and the difference between the initial and peak stages. The estimate of the parameter a for the Wilmink and Cobby models were similar as seen in the MR dataset. In general, the difference in magnitude of the estimate of a was similar between datasets.

For this dataset, the Wilmink model had the higher production at the peak and the lowest at the start of the lactation. All the models underestimate the actual peak yield value, but Wilmink model predictions were the closest ones.

Discussion

Mean yield per month

The results of the Brody's model with the lowest AIC and RMSE values for milk yield highly contrast with the findings reported for Iranian Holstein cows, where the Brody model presented the highest AIC values in comparison with the model(s). Such study was carried out with high milk-yield twinning cows (Hossein-Zadeh, 2019), and the difference may be due to production system and breed differences.

For the MR dataset, the Brody, Wilmink, and Cobby models showed similar values for the *a* estimate that stands for a scale value of the initial milk yield. The Brody and Cobby models derive from the Gaines model, which may explain this similarity. For the same estimate, the Wood model proposes a lower *a* value, though, it is known that the Wood model underestimates initial milk yield. In the same way, the model proposed by Brody overestimates this very same parameter (Gradiz et al., 2009).

The Sikka model had similar estimates as other crossbreed with Jersey cows, but in the same study, the Wilmink model was the worst fitted (Mohanty et al., 2017). The estimates obtained for the Brody and Wood models with monthly mean records were similar with other reports with Holstein crossbreed cows. Such similarities may result from the fact that the same breed is used as a base from the crossbreed in tropical and subtropical conditions (Glória et al., 2012).

This type of record is common in production units around Mexico's tropical regions, where sometimes only the weekly means or the monthly means are recorded or analyzed; in this scenario, applying a robust model like the Brody model may be useful to explain the lactation of the overall mean of production.

Total yield per month

Total milk production records in monthly intervals are useful to visualize production in one number, a common problem occurs when the month in general instead of the number of days is considered to calculate the total production on the first month of lactation, in some cases when the cow calves in the second part of the month, this shorter period is still considered to be the first month total value, which normally is a smaller production total. The previous generate some biased information that is calculated in the process of iterations in the statistical software for the first month.

In the TR data, it is evident that the Wood model underestimates the parameter *a*, which may result from the Wood proposal of a "day zero" yield, that in this case was 24.7 kg for the monthly total which is underestimating the actual value. This *a* estimate value is not logical in the biology of the lactation; however, the Wood model is considered a well-fitted model in the next stages of lactation, as can be observed through the shapes of the curves in Fig. 2. The results in TR agree with those of previous studies that indicated that the Wilmink model is the best to fit the the first lactation cows with low production when AIC is used as a goodness-of-fit test (Hossein-Zadeh, 2019).

Both datasets

The Wilmink, Wood, and Brody models are widely used in similar studies, but often the milk yield is adjusted to 305 days; nonetheless, in tropical regions, the lactation length is highly volatile, with reports of 260 days of production; the shape of the lactation curve in these environments is particular and may not fit well with the models employed for highly productive animals.

As both lactation-curve estimates for MR and TR (Figs. 1 and 2) were significant in all models with similarities in their shapes in each data set, it is hard to determine which model

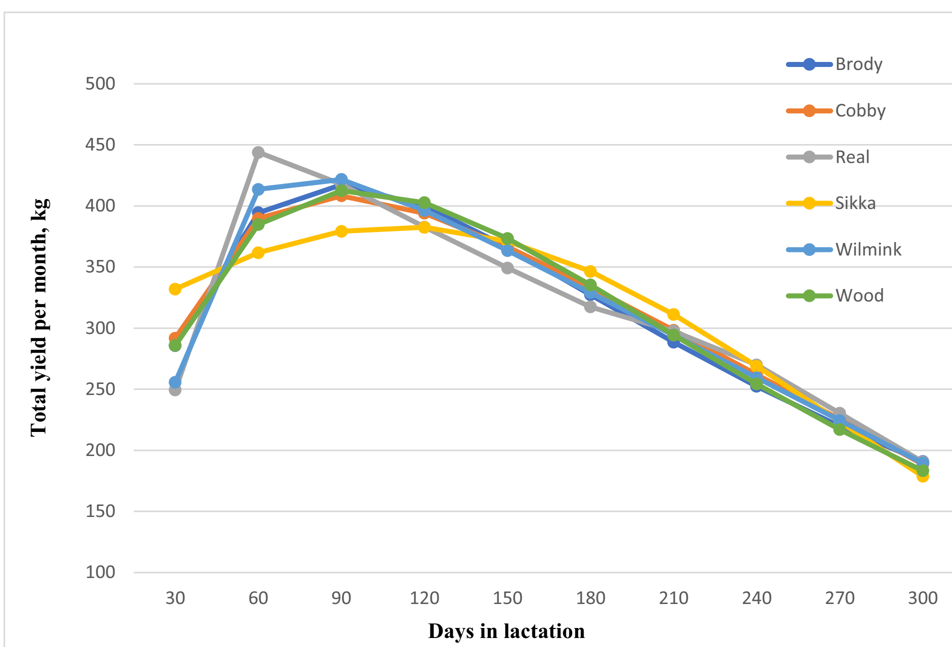

Fig. 2 Lactation-curve model comparison for total yield per month of Holstein and Brown Swiss and reciprocal crosses under subtropical conditions

is the best to use, even when their estimates may differ in each model. For both data sets, the Wilmink model was efficient in predicting milk yield, with the particularity that it had negative values on the estimates of *b* or *c*, as reported in other studies. This is caused by the estimation of parameters for this model that differ to the other models employed (Soysal et al., 2015).

In both datasets, the RMSE and AIC value proportions were alike, which indicates that the models can predict milk yield for both input data types, showing an adequate distribution of milk yield over time for this herd. In this case, the Sikka model was the worst fitted for both types of records but could be useful as a low point to compare with other models in the future.

Tested models seem to be able to predict milk-yield values with both types of datasets. As mentioned previously, missing, and inconsistent records downgrade the accuracy for building the lactation curve no matter the type of records (Hossein-Zadeh, 2014), but the tested lactation-curve models seem to be efficient to predict and construct the missing data in the lactation.

To choose the best and more applicable model to productors in the tropics is also important to notice the one that represents the best use for the parameter estimates; as is the case of the Wood model, the estimates are empirical traits of the lactation; the *b* and *c* parameters are easy to understand as the slopes between the peak of lactation; and this makes it simple to compare the estimates between animals or groups and determine the shape of lactation just by the slopes. This may be relevant in the small production type of the tropical environments, where the quick comparison of lactation may determine the strategic selection of animals and food in the short term.

In this context, it is relevant to promote the use of the Wood model instead of the ones that fitted better, because it is easier to implement outside research purposes; it could be applied easier with the small and medium milk production in the tropics, where the interpretation of the curve is analyzed by productors that may not be of statistical research intent.

Conclusions

All the studied models represent the yield increase towards the lactation peak in similar proportions with both kinds of data, either total yield records or monthly means records. The Brody model adjusted well when transformed mean data from a total month was employed. The Wilmink model was better for the estimate of the actual month total values and the actual peak yield. All the examined models proved their pertinence for the description of the subtropical lactations with different dataset records. The raw monthly or weekly data production seems to be better to define the true shape of the lactation curve than obtaining the mean values. If the model where to be employed by productors with no research purposes, the Wood model may be useful for decision-making schemes.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Hernández Zamudio Julio Antonio], [Vega Murillo Vicente Eliezer] and [Villagómez Cortés José Alfredo]. The first draft of the manuscript was written by [Hernández Zamudio Julio Antonio] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This article was funded by the National Institute for Forestry, Agricultural and Livestock Research (INIFAP) of Mexico, through the project:759434512.

Availability of data and material Not applicable.

Code availability Not applicable.

Declarations

Ethics approval All the animal studies were approved by the animal ethics committee of the INIFAP.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Akaike H. 1998. Information theory and an extension of the maximum likelihood principle. Selected papers of Hirotugu Akaike. Springer; p. 199–213.

Brody S, Turner CW, Ragsdale AC. 1924. The relation between the initial rise and the subsequent decline of milk secretion following parturition. The Journal of General Physiology. 6(5):541.

Cobby J, Le Du Y. 1978. On fitting curves to lactation data. Animal Science. 26(2):127-133.

Glória JRd, Bergmann JAG, Quirino CR, Ruas JRM, Pereira JCC, Reis RB, Coelho SG. 2012. Environmental and genetic effects on the lactation curves of four genetic groups of crossbred Holstein-Zebu cows. Revista Brasileira de Zootecnia. 41(11):2309-2315.

Gradiz L, Alvarado L, Kahi A, Hirooka H. 2009. Fit of Wood's function to daily milk records and estimation of environmental and additive and non-additive genetic effects on lactation curve and lactation parameters of crossbred dual purpose cattle. Livestock Science. 124(1-3):321-329.

Hossein-Zadeh NG. 2014. Comparison of non-linear models to describe the lactation curves of milk yield and composition in Iranian Holsteins. The Journal of Agricultural Science. 152(2):309-324.

Hossein-Zadeh NG. 2019. Application of non-linear mathematical models to describe effect of twinning on the lactation curve features in Holstein cows. Research in Veterinary Science. 122:111-117.

Janković M, Leko A, Šuvak N. 2016. Application of lactation models on dairy cow farms. Croatian Operational Research Review. 217–227.

Macciotta NPP, Vicario D, Cappio-Borlino A. 2005. Detection of different shapes of lactation curve for milk yield in dairy cattle by empirical mathematical models. Journal of Dairy Science. 88(3):1178-1191.

Melzer N, Trißl S, Nürnberg G. 2017. Estimating lactation curves for highly inhomogeneous milk yield data of an F2 population (Charolais × German Holstein). Journal of Dairy Science. 100(11):9136-9142.

Meseret, S., Tamir, B., Gebreyohannes, G., Lidauer, M. H., & Negussie, E. 2018. Comparison of test day models for first lactation milk yield in Holstein Friesian cows under tropical environment. In: Proceedings of the 9th World Congress on Genefics Applied to Livestock Producfion. 11:23.

Migose S, van der Linden A, Bebe B, de Boer I, Oosting S. 2020. Accuracy of estimates of milk production per lactation from limited test-day and recall data collected at smallholder dairy farms. Livestock Science. 232:103911.

Mohanty BS, Verma MR, Sharma VB, Roy PK. 2017. Comparative study of lactation curve models in crossbred dairy cows. International Journal of Agricultural and Statistical Sciences. 13(2):545-551.

Němečková D, Stádník L, Čítek J. 2015. Associations between milk production level, calving interval length, lactation curve parameters and economic results in Holstein cows. Mljekarstvo. 65(4):243-250.

Pereira MA, Menezes ML, Oliveira V, Lima MS, Carvalho C, Santos A. 2016. Lactation curves of crossbred Taurine x Zebu cows. Boletim de Indústria Animal.

Pollott G, Gootwine E. 2000. Appropriate mathematical models for describing the complete lactation of dairy sheep. Animal Science. 71(2):197-207.

Sikka LC. 1950. 424. A study of lactation as affected by heredity and environment. Journal of Dairy Research. 17(3):231-252.

Soysal, M. İ., Gürcan, E. K., & Aksel, M. E. H. M. E. T. (2015). The comparison of lactation curve with different models in Anatolian water buffalo. 7th Balkan Conference on Animal Science, June; 2015.

Wilmink JBM. 1987. Comparison of different methods of predicting 305-day milk yield using means calculated from within herd lactation curves. Livestock Production Science. 17:1-17.

Studies on test-day lactation milk, fat and protein yield of dairy cows PhD thesis Royal Dutch Cattle Syndicate, Arnhem, The Netherlands.41–60.

Wood PDP. 1967. Algebraic model of the lactation curve in cattle. Nature. 216(5111):164-165.