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Factors Affecting Milk Yield and Lactation Length in Sahiwal Cattle using Random Regression Model

Vinod Potdar*, Vikas Tiwari, Santosh Bansal, Sachin Joshi and Jayant Khadse

Central Research Station, BAIF Development Research Foundation, Urulikanchan, Pune, India

**Corresponding author*

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A B S T R A C T

This study investigated factors affecting milk yield and lactation length in Sahiwal cattle under smallholder dairy production systems of Uttar Pradesh, India. Test-day milk yield data from 774 animals across 14 districts were analyzed using a Random Regression Model (RRM) within a linear mixed model framework. Fixed effects included lactation number, calving year, and district, while individual animal variation was modeled as a random effect. The fitted lactation curve captured the biological pattern of rapid rise to peak yield followed by gradual decline. Significant effects of parity, year, and district ($p < 0.05$) were observed, with milk yield improving steadily from 2018 to 2025, reflecting genetic progress and improved management under the Enhance Genetics Project. District-level differences highlighted opportunities for region-specific interventions. The study demonstrates the utility of RRM for indigenous breeds, providing a robust framework for longitudinal evaluation and precision breeding. Practical implications include guiding resource allocation, improving farmer-level management, and integrating genomic data for enhanced selection accuracy.

Introduction

Milk yield and lactation length are among the most economically important traits influencing the profitability of smallholder dairy farmers in India. These traits are influenced by multiple genetic and environmental factors, including breed, parity, feeding management, season, and location (Banos and Shook, 1990; Swalve, 1995). Accurate modeling of milk yield patterns enables the identification of superior animals and aids in formulating breeding and management interventions.In Uttar Pradesh, smallholder dairy systems are characterized by 2–4 animals per household, primarily crossbred or indigenous cattle reared under low-input, resource-constrained conditions. To enhance productivity, the Enhance Genetics Project implemented by the BAIF Development Research Foundation integrates phenotypic recording, genetic evaluation, and genomic selection across multiple districts.

Such large-scale, field-based data provide valuable opportunities for analyzing factors affecting milk yield and lactation performance. Conventional lactation models often fail to capture individual animal variability or temporal trends. In contrast, Random Regression Models (RRMs) allow simultaneous estimation of fixed population trends and random individual deviations over time, thereby improving the accuracy of genetic and environmental effect estimation (Jamrozik and Schaeffer, 1997; Meyer, 1998; Schaeffer, 2004). This study utilized RRM to evaluate factors influencing milk yield and lactation performance of Sahiwal cattle in Uttar Pradesh under field conditions.

Materials and Methods

Study Area and Data Source

Data were collected from 14 districts of Uttar Pradesh — Etawah, Bareilly, Saharanpur, Varanasi, Kaushambi, Bahraich, Hardoi, Lucknow, Allahabad, Gonda, Faizabad, Pratapgarh, Rae Bareli, and Meerut representing diverse agroclimatic zones. Data recording was undertaken under the Enhance Genetics Project by BAIF.

Trained recorders collected test-day milk yield data (morning and evening) monthly for each animal, ensuring traceability through AnimalID, FarmerID, and VillageID.

Model Specification

Data analysis was conducted in R (v4.3.2) using the lme4 package. A linear mixed model was fitted with the following structure:

$$Y_{ijkl} = \mu + \text{poly(TestDay)} + \text{LactationNo}_i + \text{CalvingYear}_j + \text{DistrictCity}_k + (1 \mid \text{AnimalID}) + e_{ijkl}$$

Where:

- Y_{ijkl}= test-day milk yield,
- poly(TestDay)= 2nd-order polynomial for lactation curve,
- Fixed effects = lactation number, calving year, district,
- Random effect = AnimalID (individual animal variation),
- e_{ijkl}= residual error.

Parameter estimation was done using the Restricted Maximum Likelihood (REML) method. The significance of fixed effects was tested using Satterthwaite's approximation.

Results and Discussion

Model Performance and Variance Components

The model converged successfully (REML = 47,355.6), confirming stable parameter estimation. Variance components indicated high variability among animals:

The correlation among random coefficients (−0.29 and −0.39) suggested that cows with higher peak yield exhibited faster post-peak decline, corroborating findings by Guo and Swalve (1995) and Macciotta *et al.,* (2005).

Fixed Effects

Lactation Curve

The fixed polynomial coefficients for standardized TestDay were highly significant ($p < 0.001$), confirming a curvilinear lactation pattern characterized by an early rise, peak (30–90 days), and gradual decline consistent with Macciotta *et al.,* (2005) and Olori *et al.,* (1999). Mean yield declined from 7.70 kg (30 days) to 4.85 kg (305 days), reflecting normal biological persistency loss.

Effect of Lactation Number on milk yield

Mean milk yield increased gradually with lactation number, from 6.12 L in first lactation to 7.10 L in sixth lactation, while the CV decreased from 37.65 % to 29.98 %, suggesting improved stability in production with advancing age and parity. This reflects the physiological adaptation and enhanced mammary gland development in later lactations. Such a pattern aligns with the established biological trend where milk yield rises up to mid-lactation and then plateaus or slightly declines in older animals due to senescence (Khan *et al.,* 2018). Yadav *et al.,* (2019) also observed that crossbred cows show maximum yield during the 3rd to 5th lactation, after which a mild decline occurs. The consistent rise in yield until the 6th lactation in this study could be attributed to better longevity and genetic improvement among the crossbred herds under study. Animals in 5th and 6th lactations recorded significantly lower yields (−0.20 L and −0.48 L; $p < 0.05$ and $p < 0.001$), whereas 2nd–4th lactations showed no difference from the first. This pattern aligns with findings of Bignardi *et al.,* (2011) that productivity stabilizes in mid-parities before declining with age due to physiological wear and mammary involution.

Effect of Calving Year on milk yield

A progressive increase in milk yield was observed from 2016 (5.27 L) to 2025 (7.48 L), with a steady decline in the coefficient of variation from 42.33 % to 27.76 %. This trend signifies continuous improvement in animal performance and uniformity over the years. The improvement may be attributed to better feeding, improved genetic merit through AI programs, and enhanced record-keeping under the BAIF-supported performance recording initiatives. The marked increase during 2020–2025 indicates the positive impact of technology adoption and improved management practices at the farmer level. These findings corroborate the reports of Patil *et al.,* (2021) and Gupta *et al.,* (2023), who highlighted that genetic improvement and awareness programs led to gradual enhancement in average milk productivity in Uttar Pradesh and adjoining states. Calving year had a highly significant ($p < 0.001$) positive effect, with mean milk yield increasing from 2018 (0.26 L) to 2025 (1.88 L). The trend reflects genetic progress, better feeding, and improved management under systematic breeding programs — similar to improvements reported by Misztal *et al.,* (2000) using test-day models.

District-wise variation in milk yield

The mean milk yield across districts revealed substantial differences (Table 1). The highest average milk yield was recorded in Faizabad (8.82 ± 2.60 L) followed by Unnao (7.94 ± 2.02 L) and Lucknow (7.91 ± 2.43 L), while the lowest mean yield was observed in Bahraich (4.81 ± 2.07 L) and Bareilly (4.86 ± 1.87 L). The coefficient of variation (CV) ranged from 19.11 % (Kaushambi) to 43.06 % (Bahraich), indicating wide heterogeneity in production performance across regions. Districts such as Faizabad, Unnao, and Lucknow which recorded higher yields are characterized by relatively better management practices, feed resources, and a higher prevalence of crossbred cattle under organized breeding interventions. On the other hand, Bahraich and Bareilly regions, located in eastern and northern plains, showed lower yields due to predominance of non-descript or low-producing indigenous animals and limited access to quality inputs. These results are in agreement with earlier findings by Kakade *et al.,* (2017) and Singh *et al.,* (2020), who reported that milk yield in smallholder dairy systems in Uttar Pradesh is strongly influenced by breed type, feeding intensity, and agro-climatic variability. Similar regional variation patterns were also documented by Kumar *et al.,* (2022) in crossbred Holstein Friesian cows under field conditions. Significant district-level differences ($p < 0.001$) were observed as high-performing districts in as Faizabad (+3.16 L), Unnao (+2.85 L), Varanasi (+1.73 L), Gonda (+1.65 L) and low-performing districts as Bahraich (−1.69 L), Bareilly (−1.50 L), and Pratapgarh (−1.12 L).These differences likely stem from variation in feed availability, climate stress, and management intensity, supporting the district-wise production heterogeneity observed by Singh *et al.,* (2020) and Patel *et al.,* (2022).

Overall Model Interpretation

The RRM effectively captured both within-animal and between-animal variation in test-day milk yield, providing a biologically realistic description of lactation performance. The significant polynomial and district effects emphasize that both time-dependent physiological changes and environmental factors are key determinants of milk yield under field conditions. The observed yearly improvement indicates the success of structured breeding programs such as BAIF's Enhance Genetics initiative. In Practical Implications the model supports the use of test-day recording and RRM for longitudinal evaluation in indigenous breeds. Identification of district-level productivity gaps can guide resource allocation and training for smallholder farmers. Individual-level lactation parameters (peak yield, persistency) can be integrated into genetic evaluation for precision breeding in Sahiwal and other Indian cattle.

The analysis highlights Spatial differences underline the importance of region-specific management strategies. Temporal improvement reflects the success of breeding and extension interventions over the years. Parity-related performance emphasizes the need for sustained management to exploit the productive potential of mature animals. These findings reinforce the significance of multi-year data recording and mixed-model analysis to capture both environmental and genetic sources of variation, as suggested by Misztal *et al.,* (2019) and Strabel & Jamrozik (2020) in their random regression analyses of dairy traits.

In conclusion, Random Regression Modeling using test-day records provides a robust framework for analyzing milk yield in Sahiwal cattle under smallholder conditions. Significant effects of lactation number, calving year, and district underscore the multifactorial nature of milk production.

Table.1 Study Area and Data Source

District	Animals	Farmers	Villages	Records
Etawah	17	12	8	186
Bareilly	34	29	13	223
Saharanpur	44	36	9	506
Varanasi	45	30	14	676
Kaushambi	41	32	14	677
Bahraich	52	40	17	784
Hardoi	31	28	14	1009
Lucknow	39	20	11	1218
Allahabad	65	50	13	1291
Gonda	38	30	12	1385
Faizabad	87	44	13	1504
Pratapgarh	103	65	18	1542
Rae Bareli	79	63	21	1790
Meerut	88	75	15	2038
Total	774	565	198	14,920

Table.2 Model Performance and Variance Components

Component	Variance	Interpretation
Intercept	1.2	Baseline yield difference
Poly(1)	3360.88	Between-animal variation in curve shape
Poly(2)	821.56	Within-animal lactation persistency
Residual	1.53	Environmental and management variation

Figure.1 Effect of Lactation Number on milk yield

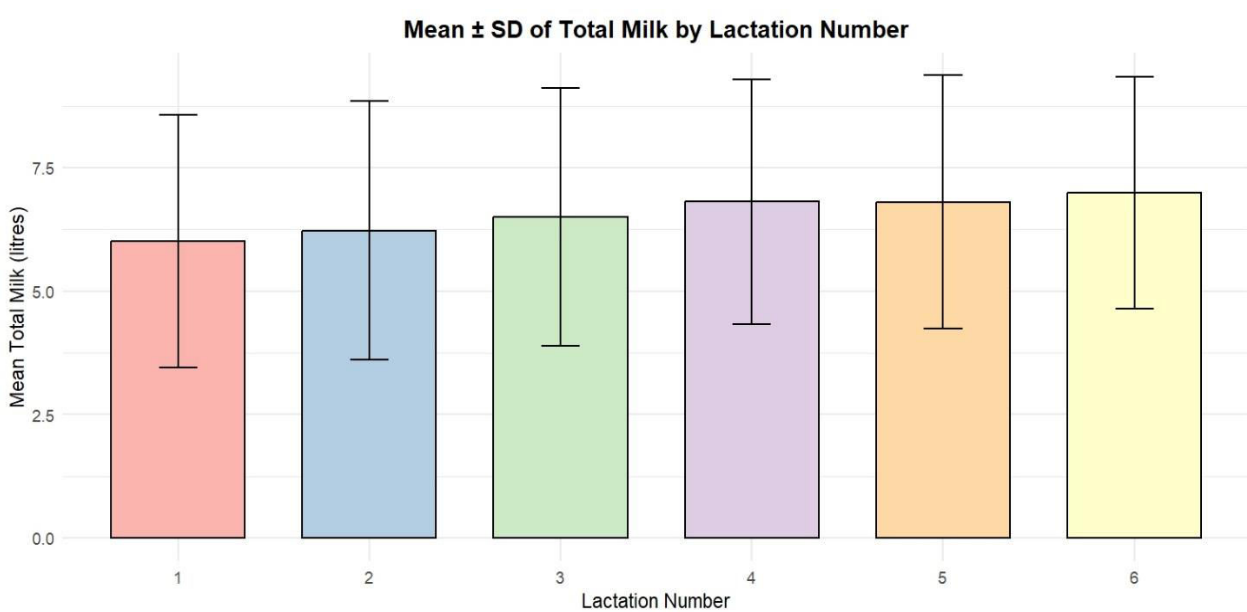


Figure.2 Effect of Calving Year on milk yield

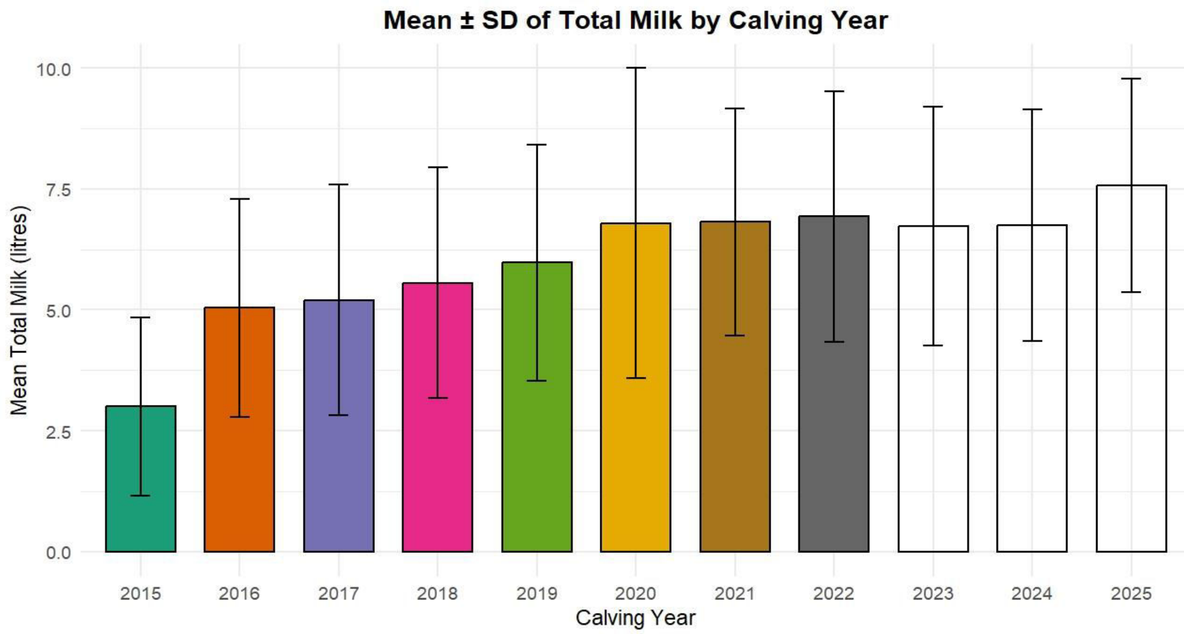
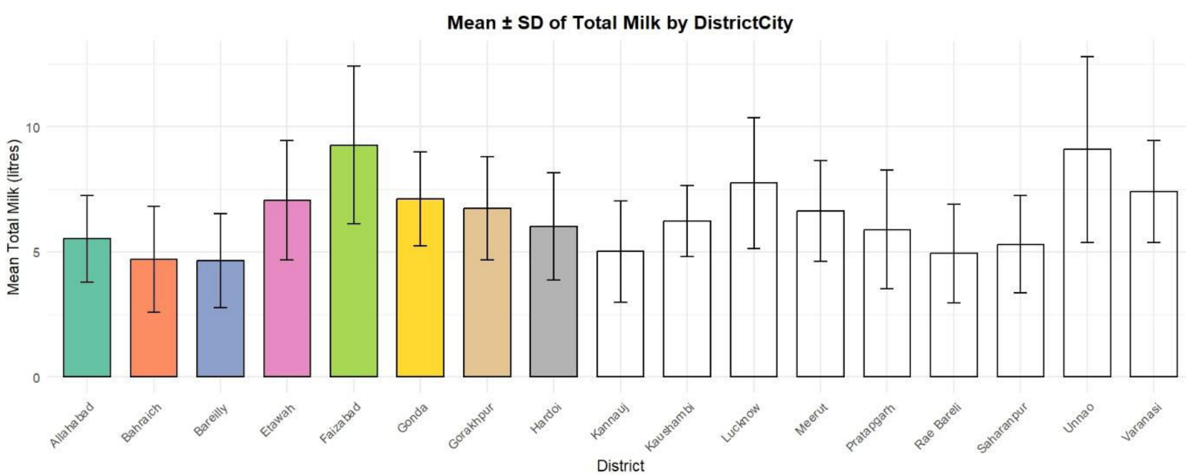


Figure.3 District-wise variation in milk yield



Temporal improvement in yield highlights the success of genetic and management interventions under the Enhance Genetics Project. Future studies integrating genomic information can further enhance selection accuracy for persistency and productivity traits in indigenous breeds.

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commitment and support were instrumental in the successful completion of this study.

Author Contributions

Vinod Potdar: Investigation, formal analysis, writing—original draft. Vikas Tiwari: Validation, methodology, writing—reviewing. Santosh Bansal:—Formal analysis, writing—review and editing. Sachin Joshi: Investigation, writing—reviewing. Jayant Khadse: Resources, investigation writing—reviewing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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