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Evaluation of reproductive traits and fertility patterns in Rohilkhandi goats using longitudinal mixed models

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Abstract

Reproductive efficiency is a major determinant of productivity in goat production systems, as traits such as litter size, kidding interval and age at first kidding directly influence lifetime reproductive output. The present study evaluated reproductive performance in Rohilkhandi goats using longitudinal and multivariate statistical approaches. Data were obtained from 1240 does maintained under organized herd conditions, with reproductive records available for up to four consecutive parities. The traits analysed included age at kidding, body weight at kidding, litter size and kidding interval. Descriptive statistical analysis indicated relatively low variability in age-at-kidding traits across parities, with the mean age at first kidding recorded as 547.09 ± 29.09 days. Body weight at kidding increased progressively with parity, ranging from 16.48 ± 0.87 kg at first parity to 25.08 ± 0.86 kg at fourth parity, reflecting normal physiological growth of does. Mean litter size increased slightly from 1.40 ± 0.49 to 1.61 ± 0.49 between the first and fourth parities, indicating gradual improvement in prolificacy. The overall mean kidding interval was 320.47 ± 14.13 days, remaining within the biologically acceptable reproductive cycle for goats. Mixed model analysis revealed moderate repeatability for litter size ($r = 0.24$) but low repeatability for kidding interval ($r = 0.11$). Random regression analysis indicated an increasing trend in litter size across early parities with stabilization around the third to fourth parity. A moderate negative correlation between age at first kidding and average kidding interval ($r = -0.576$) suggested that earlier reproductive maturity was associated with shorter reproductive intervals. Overall, reproductive efficiency in Rohilkhandi goats was influenced by parity, reproductive maturity and persistent environmental effects.

Keywords: Kidding interval, litter size, parity effects, principal component analysis, repeatability

1. Introduction

Goats represent an important component of small ruminant production systems in many developing countries, where they contribute substantially to rural livelihoods, household nutrition and income generation. Globally, the goat population exceeds 1.1 billion animals, with more than 60% of the population concentrated in Asia, where goats are mainly reared under extensive or semi-intensive production systems (Gaitri *et al.*, 2025; Meza-Herrera *et al.*, 2024) [5, 10]. India alone accounts for approximately 148 million goats, making it one of the largest goat-producing countries in the world. Their ability to adapt to diverse environmental conditions and utilize low-quality feed resources makes them particularly suitable for smallholder production systems (Department of Animal Husbandry and Dairying, 2019; Wolber *et al.*, 2021) [4, 21]. Reproductive efficiency is a key determinant of productivity and economic sustainability in goat production systems. Traits such as litter size, kidding interval and age at first kidding directly influence lifetime reproductive output and herd growth. Litter size is commonly used as an indicator of reproductive performance because it determines kid output per kidding. However, reproductive efficiency is affected by several biological and environmental factors, including parity, nutrition, body condition, management practices and genetic background. In addition, age at first kidding and kidding interval influence

the reproductive rate of females, where earlier maturity and shorter intervals are generally associated with higher lifetime productivity (Assan *et al.*, 2025; Bajaj, 2024; Simões *et al.*, 2021; Thomas *et al.*, 2016) [1, 2, 18, 20].

Reproductive traits in goats generally exhibit strong environmental influence and relatively low heritability, making genetic improvement through selection more challenging. These traits are also recorded repeatedly across successive parities, resulting in longitudinal data structures that require appropriate statistical approaches for accurate evaluation. Conventional analytical methods based on simple descriptive statistics or single-trait analyses may not adequately capture the correlated and repeated nature of reproductive records (Parsad *et al.*, 2025; Tang *et al.*, 2024) [14, 19]. In contrast, mixed model methodologies and multivariate analytical approaches enable a more comprehensive evaluation of reproductive performance by partitioning sources of variation, estimating repeatability and examining relationships among traits. Despite the importance of reproductive efficiency in goat production, information on the variability and interrelationships of reproductive traits in many indigenous goat populations remains limited. A better understanding of these patterns is essential for identifying animals with superior reproductive potential and for developing effective breeding and management strategies (Assan *et al.*, 2025; Bajaj, 2024; Parsad *et al.*, 2025; Tang *et al.*, 2024) [1, 2, 14, 19].

Therefore, the present study was undertaken to evaluate reproductive performance in Rohilkhandi goats using longitudinal and multivariate statistical approaches. The specific objectives were to: (i) describe the distributional characteristics of major reproductive traits, (ii) estimate variance components and repeatability for litter size and

kidding interval using mixed model methodology and (iii) investigate relationships among reproductive traits using correlation, principal component and cluster analyses. The results are expected to provide insights into the determinants of reproductive efficiency and support the development of improved breeding and management strategies for goat production systems.

2. Materials and Methods

2.1 Study Population and Data Source

The present study utilized reproductive records from Rohilkhandi goats maintained under organized herd conditions at the Sheep and Goat Farm, Livestock Production and Management Section, ICAR-Indian Veterinary Research Institute (IVRI), Izatnagar, Bareilly (243122), Uttar Pradesh, India. The dataset comprised records from 1240 does collected over a period of approximately 20 years, each having information for up to four consecutive parities. Animals were managed under semi-intensive production conditions where goats were allowed controlled grazing during the day and received supplementary concentrate feeding. All animals were maintained under uniform management practices including standardized feeding, breeding and health care protocols. Routine veterinary care, vaccination and deworming were conducted according to standard herd management schedules. Individual animal records were maintained for reproductive and production traits including age at kidding, body weight at kidding, litter size and parity number. These repeated records across successive parities provided a longitudinal dataset suitable for evaluating reproductive performance.

The reproductive traits considered in the study included

Trait	Abbreviation	Definition
Age of doe at kidding	A1K, A2K, A3K, A4K	Age of the doe (days) at the time of each kidding
Body weight at kidding	BW1, BW2, BW3, BW4	Body weight of doe at the time of each kidding
Litter size	LS1, LS2, LS3, LS4	Total number of kids born per kidding

2.1.2 Kidding Interval

Kidding intervals were derived from successive kidding ages as follows:

$$KI1 = A2K - A1K, KI2 = A3K - A2K, KI3 = A4K - A3K$$

Where, *KI1*, *KI2* and *KI3*: the kidding intervals between the first-second, second-third and third-fourth parities, respectively.

2.2 Derived Variables for Multivariate Analysis

For multivariate statistical analyses, the following derived variables were computed:

Variable	Definition
Average litter size (LS_avg)	Mean litter size across the four parities
Average kidding interval (KI_avg)	Mean of the calculated kidding intervals

These derived variables were used to summarize the overall reproductive performance of individual does and to facilitate multivariate analyses aimed at identifying relationships among reproductive efficiency traits.

2.3 Data Quality Control: Prior to statistical analysis, the dataset was subjected to a series of quality control procedures to ensure the reliability of the recorded observations. Reproductive records were screened for biologically implausible values and potential recording errors. Kidding intervals were examined to confirm that the values fell within the biologically acceptable range for goats.

Outlier detection for continuous variables was performed using the interquartile range (IQR) method, where the acceptable limits were defined as:

$$Lower = Q_1 - 1.5(IQR)$$

$$Upper = Q_3 + 1.5(IQR)$$

Where, Q_1 and Q_3 represent the first and third quartiles of the distribution, respectively and IQR denotes the interquartile range. Observations falling outside these limits were examined individually and retained only when they were considered biologically plausible. The distributional properties of continuous traits were assessed using the Shapiro-Wilk normality test. Missing observations were minimal (< 0.2% of the dataset) and were therefore considered unlikely to influence the overall statistical inference.

2.4 Statistical Analysis

2.4.1 Longitudinal Mixed Model Analysis: The effects of parity and year on reproductive traits were evaluated using a linear mixed model to account for repeated observations of animals across successive parities. The analysis was performed using R statistical software (version 4.3.2; R Core Team, Vienna, Austria) with the lme4 package, which is widely used for fitting linear mixed-effects models. The model was specified as:

$$y_{ijk} = \mu + Y_i + P_j + A_k + e_{ijk}$$

where y_{ijk} represents the observation of the reproductive trait for the k^{th} animal recorded in the i^{th} year and j^{th} parity, μ is the overall population mean, Y_i is the fixed effect of year of kidding, P_j is the fixed effect of parity, A_k is the random effect of animal accounting for repeated measurements within the same individual and e_{ijk} represents the residual error.

2.4.2 Repeatability Analysis

Repeatability of reproductive traits was estimated using variance components obtained from the mixed model. This analysis was also conducted using R statistical software (version 4.3.2) with the lme4 package, which allows estimation of variance components for random effects. Repeatability represents the proportion of total phenotypic variance attributable to permanent differences among animals and was calculated as:

$$r = \frac{\sigma_a^2 + \sigma_{pe}^2}{\sigma_a^2 + \sigma_{pe}^2 + \sigma_e^2}$$

Where, σ_a^2 = variance associated with the animal effect, σ_{pe}^2 = permanent environmental variance associated with the animal and σ_e^2 = residual variance.

To account for persistent environmental influences affecting repeated records of the same animal, the following repeatability model was fitted:

$$y_{ijk} = \mu + Y_i + P_j + a_k + pe_k + e_{ijk}$$

Where a_k represents the random animal effect, pe_k represents the permanent environmental effect associated with the animal and e_{ijk} represents the residual error.

2.4.3 Random Regression Model

Changes in reproductive performance across successive parities were evaluated using a quadratic random regression model implemented in R statistical software (version 4.3.2) using the lme4 package. The model was expressed as:

$$y_{ijk} = \mu + Y_i + \beta_1 Parity + \beta_2 Parity^2 + A_k + e_{ijk}$$

where β_1 and β_2 represent the linear and quadratic regression coefficients describing the effect of parity, Y_i represents the fixed effect of year, A_k represents the random effect of animal and e_{ijk} represents the residual error.

2.5 Multivariate Analysis

2.5.1 Phenotypic Correlation

Phenotypic relationships among reproductive efficiency traits were evaluated using Pearson correlation coefficients

calculated in IBM SPSS Statistics (version 26.0). Correlations were estimated among: Average litter size (LS_avg), Average kidding interval (KI_avg), Age at first kidding (A1K) and body weight at 1st kidding (BW1). These correlations quantified the strength and direction of linear relationships among reproductive traits.

2.5.2 Principal Component Analysis

Principal component analysis (PCA) was conducted using R statistical software (version 4.3.2) with the FactoMineR and factoextra packages to identify the major sources of variation among reproductive traits and reduce the dimensionality of the dataset. Prior to analysis, trait values were standardized to zero mean and unit variance to remove scale differences among variables. PCA was performed based on the correlation matrix of standardized variables. Eigenvalues and eigenvectors were calculated to determine the principal components and components with eigenvalues greater than one were retained according to the Kaiser criterion. The proportion of total variance explained by each principal component was used to identify the most influential combinations of reproductive traits.

2.5.3 Cluster Analysis

Cluster analysis was performed using R statistical software (version 4.3.2) to classify animals into groups based on similarities in reproductive efficiency traits. Both hierarchical clustering and k-means clustering approaches were applied. In hierarchical clustering, Euclidean distance was used as the similarity metric and clusters were formed using Ward's minimum variance method. The resulting dendrogram was examined to determine the appropriate number of clusters. Subsequently, k-means clustering was performed to partition animals into distinct groups based on reproductive trait profiles, allowing identification of clusters representing animals with similar reproductive performance patterns.

2.5.4 Fertility Index Construction

A composite fertility index was constructed to integrate multiple reproductive traits into a single measure of reproductive efficiency. Calculations were performed using R statistical software (version 4.3.2). Trait values were first standardized to remove scale differences among variables. The fertility index was calculated as:

$$FI = w_1 Z_{LS_avg} + w_2 Z_{KI_avg} + w_3 Z_{A1K} + w_4 Z_{BW1}$$

Where, Z_{LS_avg} = standardized average litter size, Z_{KI_avg} = standardized average kidding interval, Z_{A1K} = standardized age at first kidding, Z_{BW1} = standardized body weight at 1st kidding and w_1, w_2, w_3, w_4 represent weighting factors assigned to each reproductive trait.

The fertility index was constructed using the loading coefficients of the first principal component derived from the principal component analysis of reproductive traits. The weights assigned to average litter size (LS_avg), average kidding interval (KI_avg), age at first kidding (A1K), and body weight at 1st kidding (BW1) were 0.088, -0.699, -0.701 and 0.105, respectively. Thus, the fertility index becomes:

$$FI = 0.088(LS_avg) - 0.699(KI_avg) - 0.701(A1K) + 0.105(BW1)$$

3. Results

3.1 Descriptive Statistics of Reproductive Traits

Descriptive statistics for reproductive traits, including age at kidding, body weight of does at kidding, litter size and kidding interval, are summarized in Table 1. The mean age at first kidding (A1K) was 547.09 ± 29.09 days. The coefficients of variation for age-at-kidding traits ranged from 2.04% to 5.32%. Body weight at kidding increased with parity, ranging from 16.48 ± 0.87 kg at first parity (BW1) to 25.08 ± 0.86 kg at fourth parity (BW4). The coefficients of variation for body

weight traits ranged from 3.42% to 5.28%. Litter size across parities ranged from 1.40 ± 0.49 at first parity (LS1) to 1.61 ± 0.49 at fourth parity (LS4). The average litter size was 1.49 ± 0.50 . The coefficients of variation for litter size ranged from 30.33% to 35.02%. The kidding intervals ranged from 270 to 390 days, with an overall mean kidding interval of 320.47 ± 14.13 days. The coefficients of variation for kidding interval ranged from 8.81% to 9.81%. Skewness and kurtosis values were also calculated for the reproductive traits and are presented in Table 1.

Table 1: Descriptive statistics of reproductive traits

Trait	Mean	SD	CV (%)	Skewness	Kurtosis
A1K (days)	547.09	29.09	5.32	0.139	-1.166
A2K (days)	871.17	32.94	3.78	-0.182	-0.900
A3K (days)	1171.69	23.86	2.04	-0.892	0.025
A4K (days)	1508.49	34.96	2.32	0.295	-0.858
BW1 (kg)	16.48	0.87	5.28	0.039	-1.169
BW2 (kg)	19.34	0.88	4.54	0.126	-1.149
BW3 (kg)	22.21	0.87	3.93	0.223	-1.114
BW4 (kg)	25.08	0.86	3.42	0.327	-1.070
LS1	1.40	0.49	35.02	0.419	-1.824
LS2	1.43	0.50	34.55	0.264	-1.930
LS3	1.51	0.50	33.11	-0.039	-1.998
LS4	1.61	0.49	30.33	-0.446	-1.800
KI1 (days)	324.08	31.78	9.81	0.269	-0.904
KI2 (days)	300.52	26.48	8.81	0.960	0.171
KI3 (days)	336.80	33.01	9.80	-0.207	-1.045
KI_avg (days)	320.47	14.13	4.41	0.096	-0.359
LS_avg	1.49	0.50	33.60	0.050	-1.998

3.2 Distribution and Data Quality Assessment

Kidding intervals were calculated from successive age-at-kidding records and examined to assess the internal consistency of the reproductive dataset. Most observations fell within the biologically expected range of 270-390 days. A small number of potential outliers were detected for the second kidding interval (KI2), whereas the first (KI1) and third (KI3) intervals showed no extreme observations. Normality of the reproductive interval traits was evaluated using the Shapiro-Wilk test, which indicated a significant deviation from normality ($p < 0.001$). The proportion of missing observations in the dataset was $<0.2\%$.

3.3 Effect of Parity and Year on Reproductive Traits

The effects of parity and year of kidding on reproductive traits were evaluated using a linear mixed model, with year included as a fixed environmental factor and animal fitted as a random effect to account for repeated observations within individuals. Parity influenced litter size across successive reproductive cycles, with litter size increasing from early parities and stabilizing in later parities. Year of kidding also contributed to variation in reproductive traits. Variance component estimates and repeatability values for repeated reproductive traits are presented in Table 2. The repeatability estimate for litter size was 0.24, whereas the repeatability estimate for kidding interval was 0.11.

Table 2: Variance components and repeatability estimate for repeated reproductive traits including year effect

Trait	Animal variance	Residual variance	Repeatability
Litter size	0.045	0.140	0.24
Kidding interval	160	1240	0.11

3.4 Reproductive Trajectory across Parities

The parity trajectory of litter size was evaluated using a quadratic random regression model. The fitted regression coefficients indicated a positive linear effect of parity ($\beta_1 = 0.12$) and a negative quadratic component ($\beta_2 = -0.015$). The results indicate that litter size increased with advancing parity and approached a stable level by the third to fourth parity.

3.5 Repeatability Including Permanent Environmental Effects: To account for persistent environmental influences

across successive parities, a repeatability model incorporating a permanent environmental effect was fitted while retaining year of kidding as a fixed factor. The estimated variance components and repeatability values are presented in Table 3. The repeatability estimate for litter size was 0.37, whereas the repeatability estimate for kidding interval was 0.26. Variance components for animal, permanent environmental and residual effects are summarized in Table 3.

Table 3: Variance components and repeatability estimates including permanent environmental effects

Trait	Animal variance	Permanent environment	Residual variance	Repeatability
Litter size	0.040	0.030	0.120	0.37
Kidding interval	150	210	1040	0.26

3.6 Multivariate Analysis of Reproductive Efficiency

Phenotypic relationships among major reproductive efficiency traits were evaluated using multivariate statistical approaches. Correlation coefficients among average litter size (LS_avg), average kidding interval (KI_avg), age at first kidding (A1K), and body weight at 1st kidding (BW1) are presented in Table 5. Most reproductive traits exhibited relatively weak phenotypic correlations. The strongest association was observed between age at first kidding (A1K) and average kidding interval (KI_avg), with a correlation coefficient of -0.576 . Correlations between average litter size (LS_avg) and the other reproductive traits were low. Similarly, body weight at 1st kidding (BW1) showed minimal association with the reproductive efficiency traits considered.

Table 5: Phenotypic correlations among reproductive efficiency traits

Trait	LS_avg	KI_avg	A1K	BW1
LS_avg	1.00	-0.053	0.017	0.015
KI_avg	-0.053	1.00	-0.576	-0.003
A1K	0.017	-0.576	1.00	0.056
BW1	0.015	-0.003	0.056	1.00

Principal component analysis (PCA) was conducted to evaluate the multivariate structure of reproductive traits using average litter size, average kidding interval, age at first kidding and body weight at kidding. The first two principal components explained a substantial proportion of the total phenotypic variation, with PC1 accounting for 39.7% and PC2 explaining 25.3% of the variation. Together, these components explained 65.0% of the total variation among the reproductive traits. The projection of animals in the principal component space is presented in Figure 1.

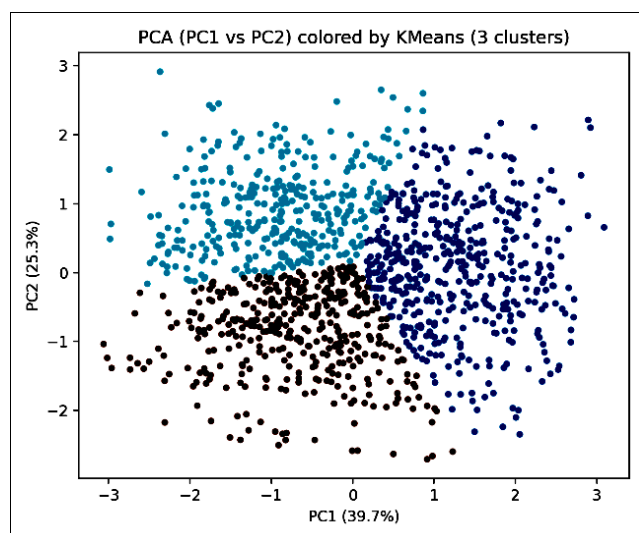


Fig 1: Projection of animals in the PCA space coloured according to K-means clustering (three clusters), illustrating classification of animals into different reproductive performance groups

Cluster analysis based on k-means classification grouped animals into three clusters based on reproductive performance traits. The clustering pattern projected onto the PCA space is illustrated in Figure 1. A composite fertility index, derived from principal component scores, was calculated to evaluate variation in reproductive efficiency among animals. The distribution of fertility index scores is presented in Figure 2.

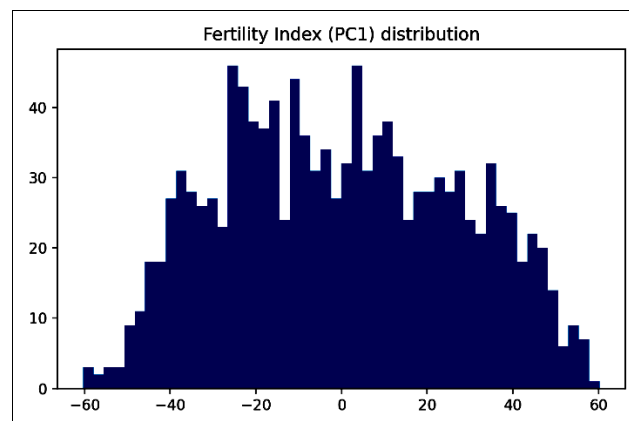


Fig 2: Histogram showing the distribution of fertility index values derived from the first principal component (PC1) of the PCA (The x-axis represents fertility index scores (PC1 values), while the y-axis represents the frequency of animals within each fertility index class)

4. Discussion

4.1 Reproductive Performance and Variability

The descriptive analysis indicated relatively low variability in age at kidding and body weight traits within the studied Rohilkhandi goat population, suggesting uniform reproductive maturity under organized herd management. The coefficients of variation for age at kidding (2.04-5.32%) indicate relatively homogeneous reproductive development among animals. Such reduced phenotypic variability is typically associated with controlled breeding systems, stable nutritional conditions and reduced environmental heterogeneity. Body weight at kidding increased progressively across parities (16.48 kg in first parity to 25.08 kg in fourth parity), reflecting normal physiological growth and reproductive maturation of does. A gradual increase in litter size across parities (1.40-1.61 kids) was also observed, indicating improved prolificacy with advancing reproductive age.

Similar parity-related increases in litter size have been reported in Boer goats, where reproductive traits were significantly influenced by parity and age of dam (Zhang *et al.*, 2009) [22]. Comparable mean litter sizes (1.70 ± 0.66 kids) were reported in Brazilian Boer goats analysed using mixed animal models (Menezes *et al.*, 2016) [9]. These findings are consistent with the present results, supporting the biological explanation that reproductive efficiency improves as does reach physiological maturity and enhanced uterine capacity. Such parity-related improvements are common in small ruminants where reproductive traits are influenced by both genetic and environmental factors (Notter, 2012) [13].

4.2 Effect of Parity and Year on Reproductive Traits

The longitudinal mixed model indicated that parity and year of kidding significantly contributed to variation in reproductive traits. Litter size increased during early reproductive cycles and stabilized in later parities, reflecting progressive reproductive maturation. The quadratic random regression model supported this pattern, with a positive linear parity effect ($\beta_1 = 0.12$) and a negative quadratic component ($\beta_2 = -0.015$), suggesting that litter size increases during early parities and reaches a plateau around the third to fourth parity. Similar effects of parity and year have been documented in Arsi-Bale goats, where parity and year significantly influenced litter size and kidding interval (Kebede *et al.*, 2012) [6]. Likewise, analyses of Boer goats using mixed models showed that parity and environmental factors

significantly affect reproductive traits, including litter size and doe weight at parturition (Menezes *et al.*, 2016) ^[9]. Environmental influences such as climate, feed availability and management conditions often cause year-to-year variation in reproductive performance. Reviews of goat reproductive systems also emphasize the importance of nutrition, seasonality and management in determining reproductive outcomes (Robertson *et al.*, 2020) ^[16].

4.3 Repeatability of Reproductive Traits

Repeatability estimates provide information on the consistency of trait expression across successive reproductive cycles and indicate the relative contribution of permanent animal effects. In the present study, litter size showed moderate repeatability ($r = 0.24$), suggesting that early parity records may provide some predictive value for future prolificacy. However, a considerable proportion of variation remains attributable to temporary environmental effects. Comparable repeatability estimates have been reported in Arsi-Bale goats, where litter size and related traits exhibited repeatability values ranging from 0.13 to 0.18, indicating moderate consistency across parities (Kebede *et al.*, 2012) ^[6]. Similarly, analyses of reproductive traits in Boer goats reported repeatability estimates near 0.1 for most reproductive traits, indicating strong environmental influence (Menezes *et al.*, 2016) ^[9]. These findings support the biological interpretation that reproductive traits generally have low heritability and moderate repeatability, reflecting strong environmental modulation (Mokhtari *et al.*, 2019; Notter, 2008) ^[11, 12]. The increase in repeatability estimates when permanent environmental effects were included in the model (0.37 for litter size and 0.26 for kidding interval) further suggests that some environmental conditions persist across parities and contribute to consistent differences among animals.

4.4 Relationships among Reproductive Efficiency Traits

Phenotypic correlation analysis revealed a moderate negative relationship between age at first kidding and average kidding interval ($r = -0.576$), indicating that animals reaching reproductive maturity earlier tended to maintain shorter reproductive intervals. This relationship suggests that earlier reproductive maturity may enhance lifetime reproductive productivity by allowing females to initiate reproductive cycles sooner. Studies on dairy goats have similarly reported relationships between reproductive traits and productivity. For example, genetic analyses of US dairy goats demonstrated correlations between reproductive traits such as age at first kidding and productive life, indicating the importance of early reproductive maturity in improving herd productivity (Castañeda-Bustos *et al.*, 2014) ^[3]. Additionally, research on Raeini Cashmere goats showed significant phenotypic and genetic correlations among early reproductive traits, including litter size and age at first kidding (Mokhtari *et al.*, 2019) ^[11]. The weak correlations observed between litter size and growth-related traits in the present study suggest that prolificacy is influenced by additional physiological mechanisms such as ovulation rate, embryonic survival, and endocrine regulation. This pattern is widely recognized in small ruminants where reproductive and growth traits may be regulated by partially independent biological pathways (Bajaj, 2024; Notter, 2012; Shokrollahi & Morammazi, 2018) ^[2, 13, 17].

4.5 Multivariate Structure of Reproductive Efficiency

Principal component analysis revealed that the first two components accounted for a large proportion of the total phenotypic variation in reproductive traits (65.0%). This indicates that reproductive efficiency in the studied population can be effectively summarized by a limited number of underlying dimensions representing reproductive maturity and prolificacy. The presence of distinct clusters identified through k-means classification suggests heterogeneity in reproductive potential within the population. Animals in the high-performance cluster exhibited relatively higher litter sizes and shorter kidding intervals, indicating superior reproductive efficiency. Such heterogeneity in reproductive performance is commonly observed in goat populations due to variation in both genetic background and environmental conditions. Studies on goat reproductive traits have also reported considerable variability in reproductive performance among individuals and herds. Large differences in reproductive outcomes among goat populations have been documented under different production systems, reflecting variation in nutrition, management and genetic factors (Robertson *et al.*, 2020) ^[16]. Similarly, genetic analyses indicate substantial diversity in reproductive potential among goat breeds and populations like Serrana Goats (Margatho *et al.*, 2019), Bohuai goats (Zhang *et al.*, 2025) ^[23] and Huang-Huai goats (Quan *et al.*, 2025) ^[8, 15]. These findings support the present results and suggest that multivariate approaches can effectively identify animals with superior reproductive profiles.

4.6 Implications for Breeding and Management

The moderate repeatability observed for litter size suggests that selection based on early parity reproductive records may contribute to gradual improvement in prolificacy within the population. However, the relatively low repeatability of kidding interval indicates that environmental and management factors play a major role in determining reproductive interval traits. Reproductive traits in goats generally exhibit low heritability and strong environmental influence, indicating that management interventions can substantially improve reproductive efficiency. Reported heritability estimates for most reproductive traits in goats typically range from 0.05 to 0.15 (Notter, 2012) ^[13], in Arsi-Bale goats, 0.060 for kidding interval and 0.074 for litter size (Kebede *et al.*, 2012) ^[6], in Boer goats, 0.10 for kidding interval and near zero for litter size, confirming strong environmental influence (Menezes *et al.*, 2016) ^[9]. These findings suggest that improvements in nutrition, health management, and reproductive management can play a major role in enhancing reproductive performance (Lianou *et al.*, 2022; Robertson *et al.*, 2020) ^[7, 16]. Furthermore, reproductive management practices including improved breeding control and health monitoring have been shown to enhance reproductive outcomes in small ruminant production systems (Lianou *et al.*, 2022) ^[7]. Therefore, a combined strategy involving genetic selection for prolificacy and improved herd management practices is likely to be most effective for enhancing reproductive efficiency and long-term productivity in goat populations.

5. Conclusion

The present study evaluated reproductive performance in Rohilkhandi goats using longitudinal mixed-model and multivariate analytical approaches. The results indicated relatively uniform reproductive maturity within the population, as reflected by the low variability observed in

age-at-kidding traits. Litter size showed a gradual increase across successive parities, stabilizing around the third to fourth parity, which reflects the influence of physiological maturity on reproductive performance. The moderate repeatability estimate for litter size suggests that early reproductive records may be useful for identifying animals with relatively superior reproductive potential. In contrast, the low repeatability observed for kidding interval indicates that this trait is strongly influenced by environmental and management factors. A moderate negative association between age at first kidding and average kidding interval suggests that earlier reproductive maturity may contribute to improved reproductive efficiency. Multivariate analyses further revealed heterogeneity in reproductive performance among animals, indicating opportunities for improving reproductive efficiency through a combination of selective breeding and improved herd management practices.

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Author contributions

Nitish Gaitri: Data Curation, Formal analysis, Writing-Original draft, Investigation. Arundhati Sharma: Formal analysis, Writing- Original draft. Subodh Kumar: Conceptualization, Supervision, Resources, Review & editing. Pushpendra Kumar, A K Pandey, Amit Kumar & Hari Om Pandey: Supervision, Conceptualization, Review & editing. Varun Jasta, Vibha Singh, Ankush Rana and Renu Motwani: Writing, Review & editing.

Ethical approval

The animal study was reviewed and approved by the Institute Animal Ethics Committee, Indian Veterinary Research Institute, India (Approval No. 26-1/2024-25/JD (R)/IAEC) dated 12/07/2024.

Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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