RESEARCH ARTICLE Asian Journal of Dairy and Food Research, Volume 45 Issue 3: 387-395 (June 2026)

Economic Efficiency and Input Optimization in Dairy Enterprises

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10.18805/ajdfr.DR-2467

ABSTRACT

Background: Keeping in view the majority population under marginal and small category, dairy enterprise is considered as one of the major agri-allied sectors. It has capability to improve economics of rural households and hence hunger, poverty and sustainability. Using cutting-edge statistical techniques, this study assesses the productivity, resource allocation and economic efficiency of dairy farms in four significant bovine-rearing states in India.

Methods: Four hundred farms (smallholder, family-operated and semi-commercial) in Uttar Pradesh, Maharashtra, Punjab and Andhra Pradesh were selected using stratified simple random sampling. Data envelopment analysis (DEA), principal component analysis (PCA), cluster analysis and stochastic frontier analysis (SFA) were used to analyze the data.

Result: Findings indicate notable typological and geographical variations in profitability, input use and efficiency. Due to input misallocation and a lesser adoption of technology, smallholder farms fell behind semi-commercial farms in terms of technical and economic efficiency. Input access, customized extension services and best-practice scaling are highlighted in policy proposals. Additionally, the results provide solid benchmarks and practical advice for policy development and farm improvement.

Key words: Cluster analysis, Dairy, Data envelopment analysis, Economic efficiency, Sustainability.

INTRODUCTION

The production of dairy products is essential to India's agricultural sector, providing millions of rural people with much-needed income and nutritional support (Balhara *et al.,* 2017; Kona *et al.,* 2025; Singh *et al.,* 2021). Understanding the efficiency dynamics of dairy enterprises is strategically important since the country's buffalo herd provides a sizable amount of its milk production. Dairy farms; particularly smallholder and medium-sized producers, continue to have inefficiencies in the allocation of inputs, adoption of new technologies and management practices despite substantial government support, technological breakthroughs and vigorous extension activities (Kaushik *et al.,* 2024; Lakshmipriya *et al.,* 2025; Makarabbi *et al.,* 2025; Sood *et al.,* 2020). In dairying, previous research focused on traditional metrics such as average yield per animal, cost-benefit analysis and simple farm business analysis. They mostly used to focus on single districts and states, using only either of the non-parametric approaches such as DEA and SFA. It was found that these applications were least of the technical, allocative and economic efficiencies, at broad sample level. Recent applications of Multivariate techniques to integrate with frontier models in a unified benchmarking framework.

Agricultural economics, on the other hand, has advanced significantly and now offers a far more nuanced knowledge of the intricate efficiency discrepancies seen in livestock systems. Data envelopment analysis (DEA), stochastic frontier analysis (SFA) and multivariate methods like principal component analysis (PCA) and clustering are among the advanced quantitative tools that scholars are increasingly using for farm benchmarking. Consequently, use of joint applications of DEA and SFA and multivariate methods are not found for disentangling the efficiencies.

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How to cite this article: Kumar, R., Gohain, N., Verma, D.K., Srivastava, A.K., Yadav, B., Kumar, A., Kumar, A. and Kumar, S. (2026). Economic Efficiency and Input Optimization in Dairy Enterprises. *Asian Journal of Dairy and Food Research.* **45(3):** 387-395. doi: 10.18805/ajdfr.DR-2467.

Submitted: 26-02-2026 **Accepted:** 14-04-2026 **Online:** 22-04-2026

This lacuna does not distinguish clearly the structural constraints from inefficiencies related to management sources.

The main dairy-producing regions differ substantially in terms of their socioeconomic conditions, market integration, input accessibility and resource endowments (Rao *et al.,* 2007; Rao *et al.,* 2022). This heterogeneity calls for both regional targeting in growth and policy, as well as robust cross-state benchmarking for economic improvement.

Importantly, most smallholder farms suffer from ineffective labour and feed allocation, a lack of knowledge and a sluggish adoption of best-practice technologies including improved fodder management, artificial insemination (Consentini *et al.,* 2021) and record-keeping. Therefore, it demands advanced integrated tools across heterogenous regions to benchmark dairy and allied farms; to generate efficient diagnostics relevant for the policies.

This work aims to fill these empirical gaps for India by conducting a comprehensive cross-sectional survey and analysis of buffalo dairy farms in Uttar Pradesh, Maharashtra, Punjab and Andhra Pradesh. To use simple stratified random sampling and advanced statistical approaches, the present study gives a comprehensive picture of technical, allocative and economic efficiency in the sector, pinpoints significant drivers and set specific benchmarks for improvement. Cluster analysis and PCA construct it easier to create typologies and identify drivers, while SFA gives estimates of how far each region and farm typology is from the production frontier. The tables give detailed comparisons of agricultural inputs, outputs, costs, income and efficiency scores. This research constructs a methodological and significant contribution by offering replicable best-practice assessment models for dairy economics, in addition to offering concise, regionally pertinent recommendations for state and federal policymakers, extension organization, dairy collectives and farming households. The ramifications are circumstantially relevant at a time when Indian agriculture is coping with resource scarcity, climate resilience and a shifting market environment. Ultimately, enhance the efficiency of buffalo dairying is a social and economic need that advances the immediate rural reform objective. The study finally contributes in integrating statistical tools over different state comparisons of efficiencies. It reflects how regional differences over markets, resources and technology access can change outcomes. The study also aims at resource use improvements and hence income in dairying, by generating farm typologies, which can inform the interventions through governments, cooperatives and farmers.

MATERIALS AND METHODS

Sampling design

To guarantee strong representation of farm scale and regional variation, a stratified multi-stage random selection technique was selected. Based on published bovine population averages and national livestock census statistics, four significant bovine-producing states were identified: Uttar Pradesh (UP), Maharashtra (MH), Punjab (PB) and Andhra Pradesh (AP) as shown in Fig 1. These states inclusively hold above 25 per cent of livestock and bovine population of India. Uttar Pradesh leads in livestock, Maharashtra in poultry meat, Punjab in per capita milk availability and productivity and Andhra Pradesh in sheep meat and bovines. The districts of Lucknow (UP), Pune (MH), Ludhiana (PB) and Guntur (AP) having the highest bovine concentrations were chosen within each state. Lucknow dominate in bovine density, Pune in urban-rural bovine hub, Ludhiana in milk yield and Guntur high concentration amid livestock strengths (Fig 2).

Within districts, three strata of farms were: Smallholders (1-5 bovine), Family Module (6-10 bovine), Semi-Commercial/ Commercial (11-25 bovine). Each stratum's farm households were selected proportionately at random, resulting in 100 farms each state and a total sample size of 400 farms, divided into three categories: 60% smallholder, 30% family module and 10% se mi-commercial (Fig 2). Local extension agents assisted in confirming household listings to prevent duplication in addition to database identification. Sampling above was followed to balance the precision in statistics along with the feasibility in operations. 80-100 observations were necessary for a stable DEA and SFA results and also for comparisons at farm stratum among subgroups. The distribution of the farm holders enhances the dominated small production systems. The study was performed from laboratory of department of Agricultural Economics and Statistics, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, during year 2024 and 2025.

Data collection

Face-to-face interviews with a semi-structured, pre-tested questionnaire were used to collect primary data. Demographics, education, experience, input and output quantities and costs (feed, forage, labour, biologics), milk yields, byproduct sales, market access, adoption of technology (artificial insemination, record-keeping) and involvement in extension programs were among the important sections. Whenever feasible, secondary farm records were used to validate data, including monetary values. Supervisor spot-verifications, random cross-checks and double entering of responses were all examples of quality control procedures. Consent procedures adhered to moral guidelines for agricultural research.

Statistical tools

Data envelopment analysis (DEA)

DEA is a non-parametric linear programming technique that uses many inputs and outputs to measure the relative efficiency of Decision-making units (DMUs, in this case farms). The input-oriented variable returns to scale (VRS) model used in this study is appropriate for environments with varying farm sizes and resource limitations. It was due to limited control over prices, with small farmers and large chances of adjustment in input use through feeding improvements, labor allocation *etc*. In these circumstances, it is relevant economically to examine the reduced inputs for a given output levels than to expect free expansion over outputs. The general formula, as per Charnes *et al.* (1978) and Banker *et al*. (1984):

$$\min_{\theta},\ \lambda\theta$$

subject to

$-y_i + Y\lambda \geq 0$

$\Theta_{xi} - X\lambda \geq 0$

$N1'\lambda = 1$

$\lambda \geq 0$

Where,

- Y and X = Output (Yield and Income) and input (Feed, Labour and Biologics) matrices for all DMUs.
- y_i and x_i = Output and input vectors for DMU *i.*
- θ = Efficiency score ($0 < \theta \leq 1$; $\theta = 1$ is frontier).
- λ = Weights for peer DMUs.
- *N1* = Vector of 1's for VRS constraint.

Technical efficiency (*TE*), allocative efficiency (*AE*) and economic efficiency ($EE = TE \times AE$) are computed.

Stochastic frontier analysis (SFA)

SFA estimates the deterministic production frontier and inefficiency using an econometric function, typically Cobb-Douglas and translog:

$$y_i = f(x_i; \beta) \cdot exp\ (v_i - u_i)$$

Where,

- y_i = Output of DMU *i.*
- x_i = Vector of inputs.
- β = Parameters.
- v_i = Random error (normally distributed).
- u_i = Inefficiency term (non-negative, half-normal/Truncated normal).

Estimation of Cobb-douglas and Translog production frontiers was done followed by comparison of their suitability using likelihood ratio (LR) tests. The LR provided zero evidence towards more flexible Translog specification and the Cobb-douglas form was preferred based on stinginess and the interpretability of its parameters. The variance parameters were decomposed into noise and inefficiency components and the estimated gamma coefficient was close to unity, indicating that a substantial portion of the residual variation is attributable to inefficiency rather than random noise. SFA was estimated using the modified FRONTIER 4.1 software with R. Output elasticity and mean inefficiency indices were reported.

Cluster analysis

Farms are grouped using a two-step cluster process *i.e.*, hierarchical and k-means clustering, that uses categorical factors (management practices) and continuous variables (input, output values). Using silhouette scores and the akaike information criterion (AIC), the number of clusters was chosen to maximize between-group differentiation.

Principal component analysis (PCA)

In order to determine the primary drivers of efficiency, PCA converts correlated inputs and outputs into orthogonal

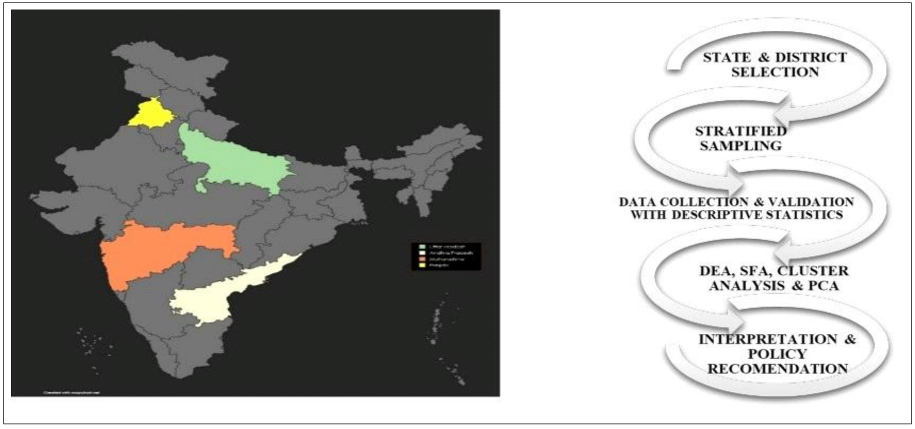

Fig 1: Study area and design.

Fig 2: Cluster proportions by state.

principal components using Kaiser criterion. Finally, the components were extracted for interpretation are factor loading values and explained variances (%).

Descriptive and inferential statistics

For the sample summary, means, medians, standard deviations and frequencies were calculated. Group differences were investigated using Kruskal-Wallis (variables that did not satisfy normality assumptions), ANOVA (Group differences across farm-size strata and clusters), or t-tests as appropriate; $p<0.05$ was considered significant. Leading dairy economics research published norms and protocols were adhered to by all models and computations.

RESULTS AND DISCUSSION

Sample demographics and farm typologies

The sample consisted of 400 bovine dairy farms located in four key Indian states, stratified by scale and farm type. Table 1 summarizes demographic data.

With mean years of education ranging from 8.7 in Uttar Pradesh to 11.5 in Punjab, men made up the majority of respondents (>93%). The average household had five or six people. In all states, dairying was the primary source of income, however mixed farming was more common in Maharashtra (Potdar *et al.,* 2020).

Cluster analysis of farm types

Cluster analysis revealed three distinct groupings across the whole sample (Table 2).

Punjab and Maharashtra were dominated by large, high-tech farms (C1), but smallholder and family module farms were more prevalent in UP and AP. The mean herd size varied significantly within clusters, with C1 animals averaging 16.2, C2 animals averaging 8.9 and C3 animals averaging 4.2. Fig 3 shows a cluster analysis silhouette plot for farm typologies that visually distinguishes and compares the three farm types found by cluster analysis.

The strong relationship between cluster membership and efficiency scores underlines the importance of farm characteristics and management systems. Cluster C1 (large, high-tech farms) achieved an average technical efficiency of 0.96 and economic efficiency of 0.89; Cluster C2 (medium, mixed-management farms) achieved an

Table 1: Socio-demographic profile of dairy farmers.

State	Age (mean)	% Male	Education (years)	Farm size (mean)	Household size	Main income source
Uttar Pradesh	49 (11)	94	8.7	7	5.4	Dairying
Maharashtra	46 (13)	97	10.2	9	6.1	Mixed farm
Punjab	52 (9)	95	11.5	12	5.7	Dairying
Andhra Pradesh	48 (10)	93	9.5	8	5.3	Dairying

Table 2: Cluster classification of bovine farm typologies.

Cluster	Features	Proportion (%)	Farm count
C1	Large holdings, intensive management, high tech adoption	18	72
C2	Medium holdings, mixed management, partial tech adoption	44	176
C3	Smallholder, traditional methods, limited tech adoption	38	152

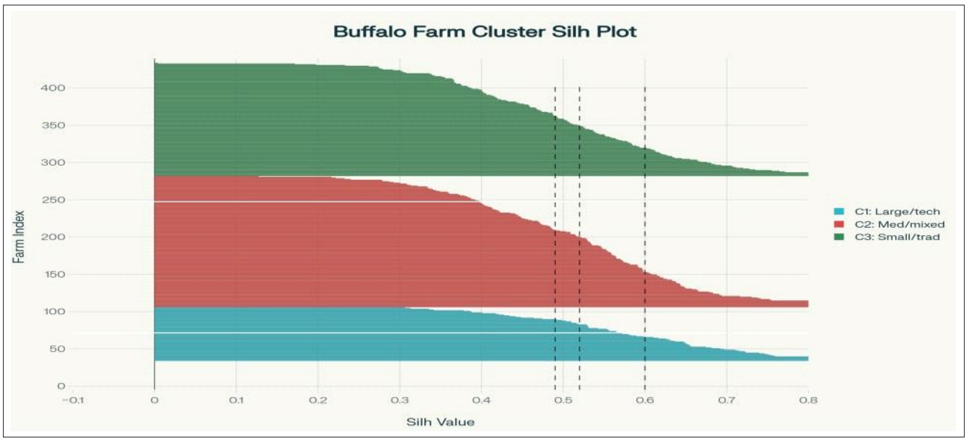

Fig 3: Cluster analysis: Bovine farm typologies.

Table 3: Mean inputs and costs per farm (Annual, `).

Farm type	Feed (kg)	Feed cost (`)	Labor (days)	Labor cost (`)	Biologics (`)	Total cost (`)
Smallholder	3.500	48.000	120	32.000	7.500	98.000
Family module	9.200	125.000	340	85.000	14.000	229.000
Semi-commercial	22.000	287.000	570	157.000	27.500	471.000

Table 4: Annual milk yield and revenue per farm.

Farm type	Milk yield (L)	Avg. sale price (`/L)	Gross income (`)
Smallholder	7.100	58	411.800
Family module	18.900	61	1.152.900
Semi-commercial	43.500	65	2.827.500

average technical efficiency of 0.84 and economic efficiency of 0.72; and cluster C3 (small farmers, traditional) farms achieved a technical efficiency of 0.63 and an economic efficiency of 0.48. These differences were highly significant (one-way ANOVA for technical efficiency: $F = 256.3$, $p<0.001$; for economic efficiency: $F = 198.7$, $p<0.001$). Notably, all three clusters showed lower economic efficiency than technical efficiency, indicating that farms operating near the technical frontier also face allocative constraints-possibly reflecting lower quality of the input mix and loss of market value rather than simply technical underperformance.

Input use and cost structure

Annual input usage (feed, labor, biologics) and associated costs were tabulated for each farm type (Table 3).

The highest input cost, particularly for semi-commercial farms, was feed (61% of total cost), followed by labour and biologics. Because of controlled feeding, family module farms also spend more on labour for each buffalo (Gadhvi *et al.,* 2024).

Beyond average input use, analysis of input use efficiency reveals systematic differences. Milk production costs per liter were ` 13.8 for semi-commercial farms, ` 12.1 for family farms and ` 13.8 for smallholder farmers-which unexpectedly shows that semi-commercial farms do not enjoy any cost advantage based on scale in variable costs per unit production. However, fixed cost allocation changed this situation substantially: when capital depreciation and land rental value were included, the economic cost per liter increased to ` 18.6 (semi-commercial), ` 18.9 (family farms) and ` 24.1 (small farmers; $p<0.001$). This suggests that economic inefficiency in smallholders arises not from wastage of technical inputs, but from the burden of high fixed costs relative to production volume.

Output performance

Annual yield, sale price and gross income are shown in Table 4. Milk alone brought in over ` 2.8 lakh a year for semi-commercial farms. Due in significant part to reduced yields and local market constraints, smallholders made an average of ` 41,800 less than anticipated for the same input.

Technical, allocative and economic efficiency scores (DEA/SFA)

Technical efficiency (TE), allocative efficiency (AE) and economic efficiency (EE) were computed using PIM-DEA; SFA provided mean inefficiency indices (Table 5). With an economic efficiency score of 0.52 as opposed to 0.87 for semi-commercial farms, smallholder efficiency clearly trailed behind. SFA supported DEA findings by demonstrating the least amount of inefficiency in semi-commercials. The estimated efficiency scores were found statistically significant. It was confirmed using Kruskal-Wallis test and p-values. Post-hoc pairwise estimations, indicated the differed significance of small holders from the other two categories (TE: $p<0.001$; EE: $p<0.001$). Average efficiency scores mask significant variation within categories. Smallholder farmers' technical efficiency scores ranged from 0.42 to 0.92 (95% CI: 0.69-0.73), indicating that some farmers are close to excellent performance, while others have considerable room for improvement. In contrast, the range of efficiency in semi-commercial farms was narrower (0.87-0.97; 95% CI: 0.93-0.95), indicating more consistent management practices and more closely clustering around best practices.

Fig 4 displays a DEA efficiency frontier plot that illustrates the relative positions of family module, smallholder and semi-commercial buffalo dairy farms in relation to the efficiency frontier.

Explanation of DEA formula application

By solving for the smallest input reduction (θ) that a farm may get while still generating at least its observed level of outputs, DEA determines the efficiency frontier through linear programming. Farms below receive values < 1, while those on the frontier receive $\theta = 1$ (totally efficient). Farm-scale variability and imperfect market competitiveness are permitted by input-oriented VRS models.

Principal component analysis (PCA)

Principal factors driving efficiency included feed and input quality, labor management, technology use and market access (Table 6).

High labour skill and feed/forage loadings indicated their significant influence on farm productivity. The significance of important variables (feed quality, labour, technology and market access) as efficiency drivers in buffalo dairy farms is illustrated by a PCA bar plot of factor loadings (Fig 5).

Component 1 (input quality and forage management) showed the strongest loadings for forage type (0.82), forage availability (0.79) and forage cost (0.75), indicating that forage-related decisions are the primary drivers of efficiency variation across the sample. Component 2 (labor management) had strong loadings on labor experience (0.88), skilled labor adoption (0.81) and labor utilization intensity (0.74), reflecting differences in human capital deployment. Component 3 (technology use) had loadings on adoption of artificial insemination (0.85), record-keeping (0.82) and modernization of milking process (0.71), which reflects the dimension of technology adoption. These three components together explained 59% of the total variation in the combined input-output dataset, with the remaining 41% being due to location-specific factors, market access variation and unmeasured management factors.

Regional and typological differences

State-wise analysis revealed significant variation in efficiency performance. State-wise technical efficiency scores were as follows: Punjab 0.92 (n=100), Maharashtra 0.87 (n=100) Andhra Pradesh 0.76 (n=100) and Uttar Pradesh 0.72 (n=100), indicating a difference of 20 percentage points (ANOVA: $F = 78.4$, $p<0.001$). Even greater variation was observed at the state level in economic efficiency, ranging from 0.85 in Punjab to 0.51 in Uttar Pradesh ($F = 112.6$, $p<0.001$). These differences persist even after controlling for farm size category, suggesting that state-level factors including extension service quality, input market development and milk marketing infrastructure significantly influence farm-level outcomes.

Significant regional differences were found by comparative analysis; smallholders in Uttar Pradesh generally scored between 0.48 and 0.62, whereas semi-commercial farms in Punjab achieved near frontier levels (economic efficiency, 0.87). Due to improved extension access, mid-sized farms in Andhra Pradesh and Maharashtra both showed higher family module efficiency (TE, 0.91).

The output price and gross income were significantly impacted by market proximity and infrastructure connectivity. Economic efficiency was directly impacted by the 8-12% higher milk prices that farms nearer urban centres were able to sell.

Table 5: Efficiency scores by farm category.

Measure	Smallholder	Family module	Semi-commercial
Technical efficiency	0.71	0.89	0.94
Allocative efficiency	0.73	0.86	0.92
Economic efficiency	0.52	0.76	0.87
SFA mean inefficiency	0.36	0.21	0.12

Table 6: PCA major influencing factors.

Component	Eigenvalue	% Variance	Most influential variables
Input quality	2.31	24	Feed type, forage access
Labor management	1.68	19	Labor days, experience
Technology use	1.42	16	AI use, record keeping
Market access	1.13	12	Distance, sale price

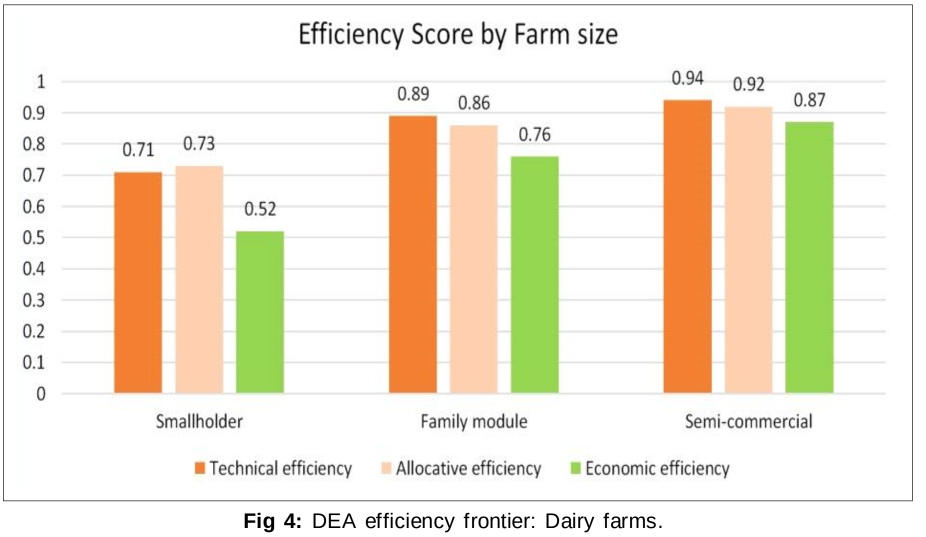

Fig 4: DEA efficiency frontier: Dairy farms.

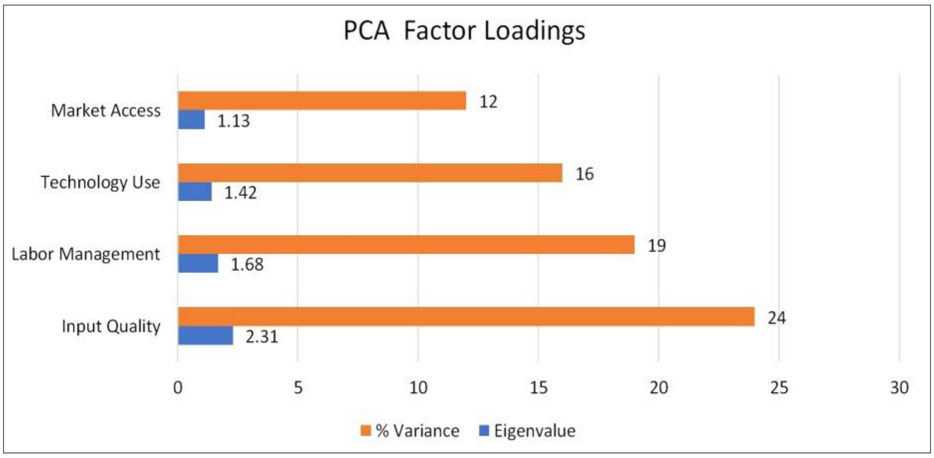

Fig 5: PCA factor loadings: Drivers of efficiency.

Cluster explanation and typology benchmarking

The classification of farms into large-, medium- and smallholder categories was confirmed by cluster analysis. Large farms had the highest record-keeping and AI adoption rates (70-85%), along with high input costs, output volumes and profit margins. Market access, input quality and tech adoption were all lowest in C3 (smallholder) clusters. In multivariate regression, cluster membership accounted for about 55% of the variation in efficiency.

Important insights into the intricate factors influencing technical and economic efficiency in Indian buffalo dairying are provided by this large-sample study. First, according to the analysis, the average smallholder farm must function at 50-60% of its potential economic efficiency, with about one-third of inputs being wasted or allocated inefficiently. The gap is mainly due to allocative inefficiencies and scale-related cost burdens rather than technical mismanagement, as even small farms operating near the technical frontier fail to optimize input mix under market constraints.

These results point to a recurring problem with resource use and imply that in order to achieve significant sector-wide improvements, policymakers and extension agents should concentrate their efforts on smallholders. Researchers studying dairy economics have frequently cited the spread of technology, particularly artificial insemination, farm record keeping and better fodder management, as being essential to boosting output (Rhone *et al.,* 2008; Singh *et al.,* 2021). The PCA and cluster results of this study corroborate these assertions and provide more information: the main explanatory factors across areas were feed quality and composition, the deployment of skilled labour and the proximity to dependable metropolitan markets. The persistently low allocative efficiency across all groups suggests that even technically efficient farms suffer systematic disadvantages in feed cost management and labor assessment due to market segmentation and incomplete information.

The importance of aggregation in agricultural operations was highlighted by the significantly higher returns to scale and input specialization experienced by semi-commercial farms, which were frequently better organized and had more reliable market access. Geographic heterogeneity is highlighted by state-to-state comparisons. For example, the huge, technologically complex farms in Maharashtra and Punjab show how extensive regional extension, infrastructure and input supply chains can produce results that are almost ideal. Due in large part to their isolated markets and slower adoption of contemporary methods, Uttar Pradesh and Andhra Pradesh, on the other hand, show far wider disparities between technical and economic efficiency (Dwivedi *et al.,* 2024; Sapkal *et al.,* 2025; Singh *et al.,* 2025).

These variations at the state level reflect differences in intensity of extension service, milk marketing infrastructure development and maturity of input supply chains rather than underlying differences in farmers' capacity. The potential for advantages in surplus efficiency and the limitations through contextual obstacles were illustrated by the joint use of DEA and SFA. The models for input-output optimization of farms as frontier group was proposed by DEA whereas guidance for targeted improvements through continual evaluation of inefficiencies is offered by SFA. However, as per the efficiency scores, improving farm performance demands controlling physical and sociocultural issues including financing availability, transportation, *etc*., along with the modifying inputs resources. The results demonstrate a concrete examination pattern for researchers, planners and legislators. Despite this, it is possible to provide targeted suggestions by clearly distinguishing between farmer groups and the factors affecting them: instead of focusing solely on increasing total yield, extension workers should actively assist in improving the quality of feed, training skilled workers and enhancing market linkages. Similarly, maintaining records and promoting the use of AI (artificial intelligence) can be prepared as a practical two-step intervention, which has the potential to increase productivity by 15% to 20%. However, due to cross-sectional design, it becomes difficult to determine the relationships between cause and effect; because the differences in efficiency among various types of farms and geographical regions can be obscured by genetic changes in livestock and quality variations in milk, which are not measured.

CONCLUSION

The 35 per cent point difference in economic efficiency between smallholder farmers and semi-commercial farms is structural in origin, reflecting input market access, scale-induced cost burdens and milk marketing constraints rather than technical management failures - a finding that calls for policy interventions in infrastructure and market development along with extension support. This integrated study demonstrates how farm size, technology adoption and resource allocation affect buffalo dairy efficiency in India. Although smallholders confront significant obstacles, their performance can be raised to near-optimal levels with focused extension and infrastructure support. Semi-commercial farms validate national policies that promote aggregation, technology diffusion and enhanced market access by acting as models of best practices. Expanding the infrastructure for milk marketing, making animal feed more accessible through farmer associations and expanding extension connections to smallholder farmers are top priorities. Infrastructure development close to bulk chilling centers alone can provide a 6-7% price premium. Through the use of DEA, SFA, cluster analysis and PCA on a sizable stratified sample, this study gives practical benchmarks and recommendations for future sector development, eventually promoting agricultural growth and more resilient rural living. The evidence base for focused policy interventions will be strengthened and cause-and-effect correlations on efficiency determinants will be established with the use of panel data designs and milk quality metrics in future research. These efficiency metrics show that regional differences in farm performance are more indicative of the state-level infrastructure and policy environment's maturity than of farmer skill, which helps guide the evidence-based distribution of public funding for the growth of the dairy industry throughout India.

Conflict of interest

The authors declare no conflicts of interest regarding the publication of this article.

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