

Original Research

Technical Efficiency, Economic Sustainability, and Environmental Implications of Dairy Farms in Pakistan

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Abstract

Dairy production is a significant contributor to food security; however, it also causes environmental problems such as greenhouse gas emissions, water pollution, and land degradation. Pakistan, a country highly vulnerable to climate change, relies heavily on its dairy sector. This sector largely consists of small farms where sustainability practices may be limited. Understanding the economic and environmental impacts of these practices on Pakistan's rural and peri-urban dairy farms is critical, yet research in this area remains scarce. This study analyzes the economic and environmental sustainability of Pakistani dairy production in rural and peri-urban areas, considering farm structure, market factors, technical efficiency, and associated policy challenges. Data from 100 farms near Lahore were analyzed using farm budgeting, Data Envelopment Analysis (DEA), and truncated regression. Results indicate that Pakistani dairy production faces limited profitability, driven largely by feed costs. Rural farms showed higher profit margins, often due to lower input costs, but were generally less technically efficient. This low efficiency carries potential environmental consequences. Truncated regression revealed that education, experience, and family size have a significant influence on technical efficiency. Findings suggest the need for targeted interventions, such as extension services tailored to the needs of rural and peri-urban farmers, promoting improved feed practices, and supporting the adoption of sustainable technologies, to enhance the economic viability and environmental sustainability of Pakistan's dairy sector.

Keywords: dairy production, technical efficiency, environmental sustainability, economic sustainability, data envelopment analysis

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Introduction

Dairy farming is a significant component of Pakistan's economy, contributing to household food security, employment, and national GDP. The livestock sector alone accounts for a sizeable 14.36% of GDP, underscoring its vital role, especially in rural livelihoods [1]. Despite this importance, the sector faces persistent challenges that limit its full potential. Low milk yields, inefficient farm management, and the increasing environmental vulnerability stemming from climate change are prime areas of concern [2, 3]. Climate change poses severe risks to dairy production in Pakistan. Research demonstrates that farmers' awareness of climate risks, their risk tolerance levels, and their access to information can significantly influence their adoption of adaptation strategies [4, 5]. For the dairy sector to realize its potential, it requires targeted interventions addressing these multifaceted challenges.

Pakistan's rapid urbanization, particularly near cities like Lahore, is profoundly transforming dairy farming landscapes. The Punjab province, where Lahore is located, accounts for approximately 62% of the country's milk production [1]. This region is experiencing significant growth in peri-urban dairy farming due to increasing demand from urban consumers. Urbanization directly increases demand for both fresh milk and dairy products, driving the growth of peri-urban dairy production zones. The proximity to these larger markets presents both opportunities and challenges for producers. Potential advantages include greater direct access to consumers and possibly higher prices, while input costs, space limitations, and regulatory complexity pose potential obstacles to successfully meeting growing urban demand. This economic shift fuels a transformation in dairy structure, evident in the increasing use of cross-breed animals as part of peri-urban intensification strategies. The shift towards cross-breeds suggests evolving farm management strategies aimed at maximizing production to meet increased market demand [6, 7].

The ongoing transformation of the dairy industry to meet increasing demand from urban consumers also introduces environmental, sustainability, and public health concerns. Intensification can sometimes lead to increased manure and water pollution if waste management is inadequate. Potential overuse of purchased feed also places extra environmental burdens on agricultural production. In addition, ensuring optimal animal health in denser production settings is vital to both animal welfare and milk safety. These challenges necessitate a deeper understanding of farm structures and practices, especially in the context of technical efficiency and sustainable dairy farming [8, 9].

In addition to the environmental impacts of the dairy sector's transformation, understanding the factors that influence technical efficiency is important for building a more sustainable system. Technical efficiency in dairy farming is essential for ensuring sustainable production

practices. Efficiency improvements are a cornerstone of responsible growth in the sector, as they directly impact both a farm's economic viability and its environmental footprint. Efficient farms not only optimize input usage and reduce costs, but also lessen environmental burdens from greenhouse gas emissions, potential water pollution, and inefficient land use [10, 11]. In the context of Pakistan, Bakhsh et al. [12] investigated the technical and environmental efficiency of bitter melon growers and found that growers can reduce the application of environmentally detrimental inputs, such as fertilizers and pesticides, without impacting yield. This finding suggests that environmentally friendly production practices can be adopted while maintaining profitability. In addition, achieving gains in farm-level technical efficiency provides environmental benefits without sacrificing farm profitability, a key consideration for making Pakistan's dairy sector both competitive and sustainable [13, 14].

Research on the interconnected environmental, economic, and social dimensions of sustainable dairy farming is scarce [15], particularly in Pakistan. This gap is most pronounced in peri-urban contexts, where studies examining economic viability alongside environmental impacts are virtually absent. This study aims to address these gaps by examining the structure, economic viability, and technical efficiency of traditional dairy farms near Lahore. A focus on farm inventories and resource use will inform an assessment of technical efficiency and its environmental implications. This comprehensive analysis aims to provide recommendations for strategies for improvement with a focus on the sustainability of Pakistani dairy farming, specifically addressing the impacts of urbanization and environmental challenges.

The rest of this paper is organized as follows: First, a literature review establishes the links between technical efficiency and environmental sustainability in the dairy sector and provides an overview of existing studies on this issue. Next, the materials and methods section explains the study area, data collection methods, and analysis tools that were used. A comprehensive results section examines both the economic viability of milk production and the technical efficiency of the surveyed livestock farms, directly exploring their environmental implications. The discussion section then analyzes the findings in the context of broader challenges and opportunities within Pakistan's dairy sector, emphasizing policy pathways that could simultaneously support enhanced farm efficiency and sustainability goals.

Literature Review

Technical efficiency (TE) plays a significant role in dairy farm profitability and directly influences the potential for optimizing resource use [16, 17]. Understanding the relationship between TE and milk

production levels is therefore of interest. While studies reveal potential links between increased production and declining technical efficiency due to higher energy use [14], there is also growing evidence that improving farm efficiency may directly reduce undesirable environmental outputs [10, 18]. In the Pakistani context, the livestock sector faces numerous challenges that hinder its potential for growth and development, such as livestock diseases, productivity issues, and supply chain inefficiencies [19-22].

Environmental factors present increasingly complex challenges to the dairy sector. Global climate change, soil degradation, and competition for finite land resources have wide-ranging implications for agriculture as a whole [23-25]. Assessing and mitigating the specific carbon and water footprints associated with dairy production represents an area of increasing importance [26]. Studies examining carbon-focused interventions, such as co-cropping or other strategies aiming for green growth, highlight the need to identify sustainable practices tailored to different production systems. Livestock diseases are a major concern in Pakistan, causing significant economic losses for farmers. Ashfaq et al. [20] found that the number of affected animals, duration of illness, nutrition costs, vaccination costs, and the occurrence of Foot and Mouth Disease (FMD) are important variables influencing these losses. Another study by Ashfaq et al. [19] revealed that the high morbidity rates of tick infestation and FMD in buffaloes and cows lead to reduced milk production, weight loss, and abortion, resulting in substantial economic losses.

Dairy farming specifically is linked to greenhouse gas emissions, including methane and nitrous oxide, along with the potential for water pollution [27, 28]. Climate change exacerbates existing challenges, including heat stress on animals, increasing feed costs, and water scarcity in many regions [29, 30]. Understanding the factors motivating the adoption of green technologies in agriculture remains important. Consumer pressure, evolving markets, and changes in policy might all influence individual producers when deciding whether and how to pursue innovations with potential environmental benefits [31, 32]. Interventions in animal health, nutrition, reproduction, and general management have been shown to enhance the productivity and profitability of small-scale dairy farms in Pakistan. Ghaffar (2016) reported that implementing such interventions can increase the overall income of the farm by 40%. These findings are supported by Ghaffar et al. [33], who conducted participatory rural appraisals and economic opportunity surveys to identify constraints and opportunities in the dairy sector. The study found that increasing milk production per day per animal through coordinated improvements in nutrition, reproduction, and genetics can maximize opportunities to enhance farmers' income.

Understanding and improving technical efficiency in dairy farming provides concrete approaches to reducing environmental impacts. Strategic interventions focused

on farm-level nitrogen management and overall herd production efficiency have the potential to lessen the sector's footprint [34]. The financial consequences of inefficient systems are evident in estimations that calculate a substantial shadow price for phosphorus surplus [35]. This reveals the potentially large economic savings possible, alongside the environmental benefits associated with technical efficiency gains. The economic performance of different dairy buffalo breeds in various agro-ecological zones of Pakistan has also been investigated. Aujla and Hussain [36] compared the costs of rearing and returns received from the Nili-Ravi and Kundhi buffalo breeds, finding that the Nili-Ravi breed is more productive and yields better returns. The study also revealed that buffalo milk production is a profitable business in most parts of the country, with feed costs occupying the majority share of the total cost of milk production.

Policy and regulatory frameworks significantly influence both technical efficiency and the environmental sustainability of dairy production systems. Strategies focusing on integrated tools can lead to reduced environmental impact and higher resource-use efficiency [37]. Research indicates that environmental policies, such as those implemented in China, can have a beneficial effect on the green total factor productivity in the dairy industry, with technical efficiency being a crucial factor in these enhancements [38]. Similarly, Berton et al. [39] reveal how policy-influenced variations in mountain dairy farming systems can directly impact environmental sustainability and resource efficiency. In addition to on-farm challenges, small-scale dairy farmers in Pakistan face difficulties in supply chain coordination and transaction costs. Ziad et al. [40] analyzed the responses of participants in informal and formal supply chains, finding a lack of coordination among small-scale farmers and associated high transaction costs. The study suggests that the illiteracy and lack of proper training among small-scale farmers, combined with the dominance of informal mid-chain agents, lead to high uncertainty and opportunistic behavior by middlemen.

The literature review shows that technical efficiency in dairy farming significantly influences both economic viability and long-term environmental sustainability. Gains in efficiency positively impact farm profitability while also reducing environmental pressures through decreases in greenhouse gas emissions, potential nitrogen pollution, and water use. Proactive policies play a significant role in promoting widespread adoption of practices that improve efficiency while safeguarding the environment. To ensure a sustainable future for the dairy sector, it is important to keep researching how to improve technical efficiency and to provide suitable policy support for farmers, as the need for dairy products keeps increasing. The studies from the Pakistani context contribute to our understanding of the economic aspects of the livestock sector, complementing the literature on efficiency and environmental implications.

By addressing the challenges identified in these studies, such as controlling livestock diseases, implementing targeted interventions, and improving supply chain coordination, the economic and environmental sustainability of dairy farming in Pakistan can be enhanced.

Materials and Methods

Data Sources and Methodology

The study area was chosen due to its significant livestock population and proximity to urban markets. Following [41], [42], a multistage random sampling technique was used to select a sample of 100 respondents from rural and peri-urban areas of Lahore. A survey instrument was developed and administered by a team of expert enumerators to collect data on livestock management practices, production costs, and revenues. The livestock farmers in the sample were categorized into two groups: rural and peri-urban farmers. The data was analyzed using descriptive statistics and farm budgeting techniques to calculate the farm gate prices and gross margins for dairy and meat production.

This study collected primary data from a sample of livestock farmers operating within the Lahore district of Punjab province, Pakistan. A sample size of 100 farmers, with equal representation from rural (50) and peri-urban (50) areas, was chosen to ensure a balanced representation of both production environments. This sample size was considered adequate for the exploratory nature of the study, which aimed to identify key factors influencing the economic and environmental sustainability of dairy farming in the region [43, 44]. Sampling targeted five towns – Ravi Town, Aziz Bhatti Town, Wahga Town, Nishtar Town, and Iqbal Town – chosen for their geographic distribution around the major urban center of Lahore.

To ensure balanced data collection, each town contributed 20 respondents, with an equal split between rural and peri-urban farms.

Peri-urban areas are transitional zones between urban and rural landscapes, characterized by a mixture of agricultural and non-agricultural land uses. These areas often experience rapid land-use changes, driven by urban expansion and increasing demand for agricultural products from nearby cities [45]. In the context of Lahore, peri-urban dairy farming has grown in response to the city's increasing demand for fresh milk and dairy products, with farmers adapting their production practices to the unique challenges and opportunities presented by their proximity to urban markets [46].

Before analyzing the data, the livestock farmers in the sample were categorized into two groups: rural and peri-urban farmers. This categorization was based on the location of the farm and the availability of land resources. Rural farmers typically have more land resources and cultivate their own fodder, while

peri-urban farmers may have limited land resources and rely more on purchased feed.

Descriptive Statistics

Descriptive statistics were used to summarize the characteristics of the sample and the livestock production practices in the study area. The mean, median, standard deviation, and range were calculated for relevant variables such as farm size, herd size, and milk and meat production.

Economic Analysis of Fixed and Variable Costs in Milk Production and Estimation of Gross Margins

In the context of evaluating the economic sustainability of dairy farming within peri-urban settings in Lahore, Pakistan, this study employs a comprehensive econometric approach to delineate the fixed and variable costs associated with milk production, subsequently estimating the gross margins. This analysis is pivotal for understanding the financial viability of dairy enterprises, taking into account the diverse economic pressures they face.

Fixed Costs (FC)

Fixed costs encompass expenditures that remain constant regardless of the level of production. In this study, fixed costs include the depreciation (*Dep*) of dairy infrastructure (*DInfra*) and livestock (*LS*), as well as the interest (*Int*) on invested capital in livestock and dairy facilities. The inclusion of depreciation in the fixed costs allows for a more accurate representation of the long-term financial sustainability of dairy farming in the study area, as it accounts for the cost of replacing assets over time [47]. The depreciation of dairy assets is calculated as a percentage of their initial value, adjusted annually, while the interest reflects the opportunity cost of capital invested in these assets. The formula for estimating fixed costs is articulated as:

$$FC = Dep_{LS} + Dep_{DInfra} + Int_{LS} + Int_{DInfra} \quad (1)$$

where Dep_{LS} and Dep_{DInfra} are the depreciations on livestock and dairy infrastructure, respectively, calculated at a rate of 5.5% per annum, and Int_{LS} and Int_{DInfra} represent the interest on the average value of livestock and dairy infrastructure, estimated at an opportunity cost rate of 12-14%.

Variable Costs (VC)

Variable costs are directly correlated with the level of production and include expenditures on fodder (both self-grown (SGF) and purchased (PF)), concentrates (C), healthcare (HC), labor (L), breeding (B), and electricity (E). The aggregate variable cost is a function of the

quantity of inputs and their respective market prices. The formula for calculating variable costs is given by:

$$VC = (SGF_{Qty} + PF_{Qty}) \times F_{Price} + C_{Qty} \times C_{Price} + HC + L + B + E \quad (2)$$

where F_{Price} and C_{Price} represent the market prices of fodder and concentrates, respectively.

Gross Margin (GM)

The gross margin is a critical indicator of the profitability of dairy farming, representing the difference between total revenue (TR) and total variable cost (TVC). It is calculated as follows:

$$GM = TR - TVC \quad (3)$$

Total revenue is derived from the sale of milk, by-products such as dung (FYM), and any income from the sale or capital gain of dairy animals. The formula incorporates the total milk production (TMP) valued at the prevailing market price per liter (P_{Milk}), income from by-products (IB), and income from the sale of dairy animals (IDA):

$$TR = (TMP \times P_{Milk}) + IB + IDA \quad (4)$$

This econometric framework enables a detailed analysis of the cost structure and profitability of dairy farming in peri-urban Lahore. By quantifying these economic factors, the study seeks to focus on the challenges and potential improvements within the dairy sector, informing the discussion on sustainable agricultural practices in Pakistan.

Estimating Technical Efficiency in Dairy Production Using Data Envelopment Analysis

The estimation of efficiency in dairy farming can be approached through two methods: the production function approach and the frontier approach. The production function approach involves calculating an average production function, often using the Cobb-Douglas model. This method compares the marginal value product (MVP) of each input with its marginal factor cost (MFC). If the MVP is not equal to the MFC, it suggests that the input is not being used efficiently [48]. However, the average production function approach has been criticized for its reliance on neo-classical assumptions that may not be applicable to traditional agriculture, such as perfect knowledge and operation in a perfectly competitive market [49]. It has also been criticized for its potential for multicollinearity and simultaneous equation bias [50].

The frontier approach aims to address these issues. It can be further divided into parametric and non-parametric models. Parametric models, such as

deterministic and stochastic frontiers, are based on specific functional forms. The stochastic frontier approach has been widely used to estimate agricultural production efficiency, but it has been criticized for its assumptions about functional form and the error term. Non-parametric models, such as Data Envelopment Analysis (DEA), are based on mathematical programming techniques and do not rely on specific functional forms. DEA has several advantages for estimating efficiency, including the ability to handle multiple inputs and outputs without aggregation bias, the lack of assumptions about functional form or error term distribution, and its suitability for small sample sizes [51]. In this study, DEA is used to estimate efficiency through the use of the variable returns to scale model, which aims to minimize inputs while still being able to produce the original output bundle. This is done by constructing a virtual decision-making unit (DMU) for each real DMU in the sample and comparing the two to determine their differences. The DEA model is formulated as follows:

$$DF^L(x, y) = \text{Min } \phi_k^{VRS} \{ \phi_k^{VRS} \geq 0 \}; \quad (5)$$

Subject to:

$$\begin{aligned} \sum_{k=1}^K \lambda^k y_m^k &\geq y_m^* & m = 1, \dots, M \\ \sum_{k=1}^K \lambda^k x_n^k &\leq \phi_k^{VRS} x_n^* & n = 1, \dots, N \\ \sum_{k=1}^K \lambda^k &= 1, \lambda^k \geq 0 & k = 1, \dots, K \end{aligned}$$

In this model, DF^L is the Debreu-Farrell input-oriented efficiency measure. The inputs of the k th decision-making unit (DMU) are multiplied by the parameter ϕ_k^{VRS} to scale them down by the smallest possible factor while still being able to produce the original output bundle. This creates a virtual DMU for each real DMU in the sample, which is then compared to the real DMU to determine the difference between the two. The parameter ϕ_k^{VRS} is the Farrell technical efficiency measure of the k th DMU under VRS, and λ is a $(K \times 1)$ vector of weights attached to each of the DMUs. The asterisk defines the DMU under investigation. The first constraint requires that the weighted average of the outputs of the reference set must be equal to or greater than the output of the DMU being evaluated. The second constraint requires that the weighted average of the inputs of the reference set must be equal to or less than the input of the DMU being evaluated, multiplied by the efficiency score. The third constraint requires that the sum of the weights must equal 1 and that all weights must be greater than or equal to 0.

Agricultural production often does not experience proportional increases in output with input increases. For example, increasing the amount of fodder given to livestock may not result in a linear increase in milk production. This is why the variable returns to scale option was more appropriate for this study. In addition, Coelli et al. [52] suggest that using the Constant Returns to Scale (CRS) method to estimate technical efficiency is only accurate when all firms are operating at optimal scale, which is often not the case due to factors such as financial constraints and imperfect competition. Using CRS to estimate technical efficiency can result in measures that are confounded by scale inefficiencies. The variable returns to scale (VRS) specification allows for technical efficiency measures that are not influenced by scale inefficiencies.

The above model is an input-oriented model, which means that the inputs are minimized to produce the original output bundle. The output-oriented model can also be used, in which case the outputs are maximized for a given set of inputs. The choice between the two models depends on the research question and data availability. In this study, inputs such as the cost of fodder, labor costs, concentrates costs, healthcare costs, electricity costs, breeding costs, and fixed costs were considered. These costs were all per farm figure. The quantities and prices of different outputs by livestock farms were obtained, and total output was converted into monetary terms for easier comparison across farms, following the methods of Speelman et al. [53] and Frijia et al. [54]. The main output used was total revenue per dairy farm.

Investigating Determinants of Technical Efficiency Using Single Bootstrap Truncated Regression

Truncated regression is a statistical technique that is used to analyze data in which the dependent variable is restricted to a certain range. In the context of our paper, we used truncated regression to investigate the determinants of technical efficiency as measured by Data Envelopment Analysis (DEA).

Tobit regression is the most commonly used approach for this purpose [53, 55-58]. However, some researchers have argued that efficiency scores are not censored values, but rather fractional values [59]. In this case, Ordinary Least Squares (OLS) in a second stage may yield more consistent results [59, 60].

However, Simar and Wilson [61] have pointed out that the conventional approaches to inference in two-stage efficiency are invalid due to the complex and unknown serial correlation among estimated efficiencies and the lack of information about the data generating process. Tobit models assume that the underlying process generating the data is normal and homoscedastic, which may not be the case with efficiency scores derived from DEA. They demonstrated that in the second stage, single bootstrap truncated regression yields more consistent results. Truncated regression is preferred over the tobit model in this study due to its ability to handle

the complex and unknown serial correlation among estimated efficiencies and the lack of information about the data generating process [61]. In contrast, truncated regression does not rely on such assumptions and can provide more consistent estimates in the second stage of the efficiency analysis [61, 62]. Therefore, we chose to use a single bootstrap truncated regression to identify the determinants of technical efficiency in our study. The general form of the estimated specification for the regression model is as follows:

$$y_{j0} = a_i + \sum_{i=n} (\beta_i Z_i + \varepsilon_i \geq 0; \text{ for } i = 1, 2, \dots, N \text{ and } \varepsilon_i \rightarrow N(0, \sigma^2) \quad (6)$$

where, y_{j0} is technical efficiency, Z_i is the set of explanatory variables, and ε_i is the error term.

Results

Socioeconomic Characteristics of Livestock Farmers

This section examines the demographic and socioeconomic characteristics of dairy farmers, exploring how these factors influence the economic and environmental sustainability of dairy production in peri-urban and rural Lahore, Pakistan. This analysis will identify potential areas for targeted policy interventions and support mechanisms.

The analysis in Table 1 reveals marked differences in farmers' age, education, and farming experience, suggesting these factors influence the adoption of sustainable farming practices. The substantial average farming experience highlights the potential for accumulated knowledge and practices to impact economic and environmental outcomes. Rural farmers generally have more crop farming experience than peri-urban farmers, likely due to greater land availability in rural areas compared to the scarcity of agricultural land near urban centers.

Education levels, while generally low, are slightly higher in rural areas. This may reflect a greater reliance on diverse agricultural skills by the rural population. Conversely, lower educational attainment in peri-urban areas could hinder the adoption of innovative and sustainable farming techniques.

Differences in family structure and size point to social dynamics potentially affecting farm labor and decision-making. Rural families are larger, with more working-age members compared to peri-urban households. The prevalence of nuclear families in rural areas could indicate reduced labor availability and shifts in farm management. Extended families in peri-urban areas may provide a larger workforce but also increase household financial pressures.

Data on primary occupations emphasizes the dependence on farming in both areas. A majority of

Table 1. Comparative socioeconomic and demographic profiles of dairy farmers.

Characteristic	Rural	Peri-urban
Age (Years)	43.48	42.56
Education (Years)	4.88	3.30
Agricultural Experience (Years)		
- Crop Farming	21.70	13.82
- Livestock Farming	23.64	21.78
Family Structure (%)		
- Nuclear	52	48
- Joint	40	34
- Extended	8	18
Total Family Size (No.)	9.58	8.50
Family Members by Age and Gender		
- Below 10 Years		
-- Males	2.26	2.55
-- Females	2.53	2.20
- Above 10 Years		
-- Males	3.47	3.23
-- Females	3.00	2.43
Primary Occupation (%)		
- Farm	84	62
- Non-Farm	16	38

both rural (84%) and peri-urban farmers (73%) identify farming as their primary income source. However, a substantial portion of peri-urban farmers (38%) engage in non-farm work, likely due to urban proximity offering alternative income opportunities. This diversification contrasts with the more singular reliance on farming found in rural areas.

These results provide a demographic and socioeconomic profile of the dairy farming community. This data supports the study’s focus on the relationship between farmer characteristics and sustainable practices, emphasizing the importance of policies responsive to the specific needs and capabilities of farming communities to promote sustainable agricultural development in Pakistan.

Dairy Farming Cost Structures, Profitability, and Implications for Sustainability

The analysis of milk production costs and revenues reveals the significant economic challenges and potential strategies for improvement in traditional livestock farming. Understanding the primary cost drivers, profitability differences between rural and peri-urban farms, and how these factors relate to the sustainability of the dairy sector is important. The analysis of the data presented in Table 2 indicates considerable variation in the economic viability of these operations. Exploring the causes of these differences provides a basis for developing targeted interventions that could enhance profitability and support Pakistan’s broader dairy sustainability goals.

Fodder and concentrates represent the most significant expenditure for both rural and peri-urban dairy farmers. This emphasizes the importance of feed management strategies for the sector’s economic viability. Labor costs, exhibiting variation between rural and peri-urban farms, remain a significant expenditure. This variation implies the potential for differences in labor use patterns and efficiency across production systems. Rural farms demonstrate higher gross margins, mainly due to higher milk revenues. This could be attributed to greater milk production, access to more favorable pricing, or a combination of these factors. In addition, rural farmers derive a larger portion of their income from livestock sales, farmyard manure (FYM), and other related sources, indicating potentially greater farm diversification.

Table 2. Cost composition in dairy farming (Rs./farm/year).

Category	Metric	Rural Farms	Peri-urban Farms	Average
Cost Composition	Fodder and Concentrates	353,660	400,324	376,991
	Labor	43,879	13,540	28,709
	Healthcare, Breeding and Electricity Cost	10,057	10,639	10,348
	Fixed Costs	50,812	53,218	52,015
	Total Costs	458,408	477,721	468,063
Dairy Farming Gross Margins	Milk Revenue	840,949	666,370	753,659
	Additional Revenue (Animals, FYM, Capital Gains)	83,709	84,234	83,972
	Total Revenue	924,658	750,604	837,631
	Gross Margin	466,251	272,884	369,568

These results reveal that urban farmers may face difficulties due to limited land for fodder production and higher input costs. But they could also gain from their proximity to urban markets, which could influence the prices they can charge for their milk. These results indicate the need for interventions to improve feed utilization and cost-effectiveness in the dairy sector. Addressing this area is likely to improve overall farm profitability, impacting environmental sustainability through reductions in potential overgrazing or overuse of purchased feed. Furthermore, recognizing the different profitability levels between rural and peri-urban environments suggests the need to design policies for the sector with appropriate specificity. Instead, support mechanisms need to consider the specific challenges and opportunities that exist for farmers in each context.

Optimizing Input Use in Livestock Production: Technical Efficiency Results

Technical efficiency (TE) in livestock farms was assessed using an input-oriented bootstrapped Data Envelopment Analysis (DEA) model. Results (Table 3, Fig. 1) indicate significant potential for improvement. An overall mean efficiency of only 32% signifies that many farmers may use inputs in excess of the levels needed for current output levels. Notably, 18% of farms operated at less than 20% technical efficiency, suggesting they could greatly reduce input use without impacting production. Further, only 11% operate above 50% efficiency.

These findings directly impact economic and environmental sustainability. Farms operating inefficiently may experience lower profitability due to excess input costs. Environmentally, inefficient resource use, particularly related to feed or water, raises concerns about potential waste and pollution. Identifying the

Table 3. Distribution of technical efficiency levels among dairy farms in peri-urban Lahore.

Technical Efficiency (%)	No. of Farmers	Percent	Cumulative Percent
<20	26	18.3	26.0
20-30	17	12.0	43.0
30-40	15	10.6	58.0
40-50	16	11.3	74.0
50-60	14	9.9	88.0
60-70	10	7.0	98.0
70-80	1	.7	99.0
80-90	1	.7	100.0
90-100	0	.0	100.0
Mean Efficiency	0.322		

specific factors influencing this low efficiency becomes essential for enhancing both the economic viability and environmental performance of the livestock sector. It is likely that improved management practices, technological adoption, or farm-specific production adjustments could significantly enhance productivity without necessitating proportionate increases in inputs.

Determinants of Technical Efficiency in Dairy Farming and Implications for Sustainability

Understanding the factors that influence technical efficiency is essential for designing interventions to improve resource utilization and reduce waste in the dairy sector. The following truncated regression analysis identifies specific drivers of efficiency differences within

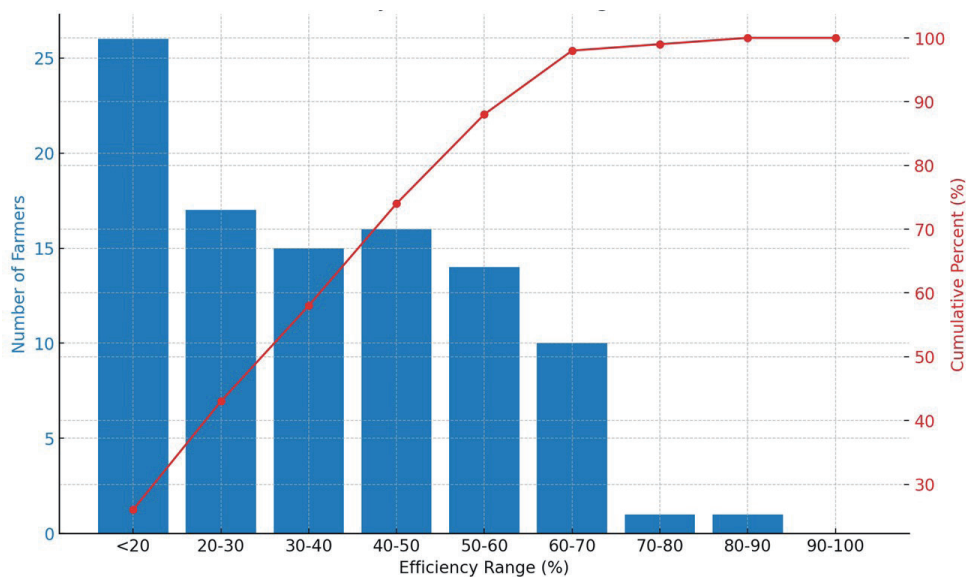


Fig. 1. Technical efficiency distribution among dairy farmers in rural and peri-urban areas of Lahore.

your surveyed farms. The regression results (Table 4) reveal statistically significant relationships between technical efficiency and several farmer and farm characteristics. Farmers focusing primarily on livestock farming demonstrate higher technical efficiency than those with non-farm occupations. This could be because dedicated livestock farmers have likely developed specialized knowledge and practices, allowing them to optimize inputs. Diversification into non-farm work may split a farmer’s time and focus, potentially hindering efficiency.

Experience significantly influences efficiency - those with longer farming histories display greater efficiency. Accumulated knowledge likely results in more effective resource management and better optimization of farm operations. Larger family sizes correlate with lower technical efficiency. While providing potential labor inputs, larger families may strain farm resources or result in less streamlined decision-making processes, impacting efficiency. Surprisingly, unrestricted access to water is positively associated with efficiency. This suggests potential differences in water use management where unrestricted access incentivizes careful utilization. Conversely, paying for water could lead to less strategic or less efficient use.

It’s worth noting that education level, cultivable area, off-farm income, and loan access did not show a statistically significant impact on technical efficiency in this analysis. This underscores that improving

efficiency is a complex matter not directly associated with any single factor.

These findings have clear sustainability implications. Enhancing efficiency directly reduces input waste, resulting in less environmental strain from unnecessary feed production, potential overgrazing, water pollution, or inefficient animal production. Policies, training programs, and knowledge sharing focused on boosting efficiency should align with the needs and contexts of individual farms to be effective. For example, initiatives designed to support less experienced farmers, or those relying on both farm and non-farm income, may need specific strategies for boosting their operational efficiency.

Discussion

This thorough research on dairy production and its sustainability implications in the outskirts and countryside of the Lahore region reveals how social, economic, farm management, income, and environmental aspects are related. These links can inform policy and program development that promote sustainable progress in Pakistan’s milk industry.

Several socioeconomic characteristics emerged as influencing factors related to sustainability. Rural farmers’ generally greater emphasis on crop cultivation likely stems from larger landholdings, leading to diversification but also possibly less focus on optimizing dairy input usage. Conversely, peri-urban farmers’ often smaller landholdings may drive specialization in dairy, enhancing efficiency in some cases but also raising input cost concerns [63]. Education levels, while low overall, are higher in rural settings. This, combined with longer rural farming experience, suggests stronger potential for accumulated agricultural knowledge in rural areas. However, extension services tailored to the specific needs of rural and peri-urban farmers could bridge existing gaps, focusing on sustainable intensification and optimal feeding practices [64].

Family dynamics also play a role. While rural families offer larger potential labor pools, this does not guarantee streamlined processes and decision-making. Extension services, including women-focused training, could optimize this labor, as could targeted mechanization support where beneficial. Peri-urban farms’ smaller, yet often extended, family structures require different types of labor utilization strategies [65]. Importantly, reliance on farming as the primary income source demonstrates the dairy sector’s critical role in both locations. Strategies must therefore promote viable economic returns. Peri-urban farmers’ greater non-farm income engagement necessitates different support pathways that acknowledge time constraints while leveraging proximity to potential markets.

Feed and concentrate costs are the main factors that affect the economic situation of dairy farming, which means the sector is sensitive to changes in input

Table 4. Truncated regression estimates of determinants of technical efficiency in dairy farming.

Variable	Coefficient
Primary Occupation (0 = Farm, 1 = Non-Farm)	-0.0949** (0.0524)
Education (years)	0.0079* (0.0049)
Livestock farming experience (years)	0.0028* (0.0016)
Family size (No.)	-0.0107*** (0.0046)
Cultivable area (acres)	0.0018 (0.0015)
Off-farm income (0 = no, 1 = yes)	-0.0319 (0.0506)
Unrestricted water access (0 = no, 1 = yes)	0.0814* (0.0476)
Loan (1 = yes, 2 = no)	0.0275 (0.0592)
(Intercept)	0.2632* (0.1643)
Log Likelihood	9.9491

Notes: Standard statistical notations apply: * (p<0.10), ** (p<0.05), *** (p<0.01). Standard errors are shown in parentheses.

prices and availability. Strategies that aim to improve feed efficiency, such as using improved forage methods and spreading knowledge on low-cost feed alternatives, could lower these costs significantly. Furthermore, rural farms may have relatively higher margins because of scale benefits, diversification options, or better negotiation with milk buyers. This indicates possible areas for intervention to improve the economic sustainability of peri-urban dairy farms, such as forming producer groups or accessing processing facilities [66, 67].

Technical efficiency emerges as a critical factor influencing both economic and environmental sustainability in dairy farming. Specialization in livestock, coupled with access to relevant knowledge and technologies, can drive improvements in efficiency. This is particularly important for less experienced farmers or those balancing farming with off-farm income sources, who may require support specific to their unique circumstances [15, 68].

Larger family size negatively impacting efficiency isn't necessarily a call for smaller families, but instead reflects the need to strategically use farm labor as it grows. Women-focused training could be beneficial, alongside exploring mechanization in ways that don't reduce employment but do make it more effective. The positive connection between unrestricted water access and efficiency seems counterintuitive until context is considered. Where resources are unrestricted, careful management for animal health and productivity is likely to become paramount [69, 70]. This finding deserves further study regarding its economic and environmental implications.

These findings emphasize that no single intervention will transform the dairy sector. Effective policy must combine approaches targeting the varied constraints on farm efficiency. Access to extension services disseminating appropriate practices is essential but must be matched by the potential to implement them. This could range from knowledge delivery on low-cost feeds to facilitating cooperative input purchasing for the most vulnerable farms. Strengthening farmer organizations will enhance farmers' negotiating power for both higher milk prices and greater influence on policies impacting their operations. Lastly, continued research is essential to address specific regional challenges and ensure the long-term environmental viability of dairy production [71-73].

Conclusion and Policy Implications

This study has shown that traditional dairying in the Lahore region is mostly done by small farmers. In addition, we also found that most of these farmers depend on livestock as their main source of income. Findings further reveal that, generally, the farmers have low education levels, and they may tend to use methods that are less eco-friendly than modern ones. In line with previous studies done in African peri-urban pig-keeping

systems, feed and concentrate costs took up a large part of the production costs, while profitability was partly affected by the variability differences between peri-urban and rural farms. This finding calls for designing interventions that improve the economic outcomes of farmers while, at the same time, the sector becomes more environmentally sustainable.

Our study also shows that the sector has low overall technical efficiency, which has huge implications for sustainability and the environment. This means that many of the farmers could use much fewer inputs to produce the same outputs. In other words, there is potential to reduce waste and the environmental impact of production. Therefore, policies that help farmers overcome barriers to efficiency are important for the peri-urban livestock sector. This could include creating awareness about how to optimize feeding and resource management or supporting those farmers who face specific challenges. These policies would also benefit farm profitability, as well as reduce excess use of fertilizers, potential grazing stress, and inefficient water use. In addition, efforts that lead to specializations in livestock would improve efficiency, but they should consider the different constraints and income sources of many households. Policies that encourage farmer cooperation for learning exchange and joint input purchases could increase the effectiveness of limited resources invested in the extension staff. Exploring the implications of water use patterns further may identify water-smart practices beneficial across farm scales.

The study recommends making the Punjab dairy sector more sustainable and productive through a balanced approach to economic and technical programs. This will promote adoption and economic feasibility in the country so that the dairy sector benefits farmers, consumers, and the environment in the future.

This study makes a significant contribution to the topic of the economic and environmental sustainability of dairy farming in Punjab, Pakistan, but it also has its limitations that need to be recognized. The data are based on self-reports from farmers, which may be affected by memory errors and social desirability bias. Also, the data are cross-sectional, which limits the possibility of establishing causal connections between the factors considered and the economic and environmental results of dairy farming.

These limitations imply that future studies should use more objective methods of data collection, such as direct observation or longitudinal surveying, and reduce the biases as much as possible while also capturing the dynamic changes of time in farming practices and sustainability. More research is needed to explore the role of some of the institutional factors, for example, access to extension services, credit, and markets, in influencing the decisions and outcomes of farmers regarding their sustainable dairy farming practices. Future studies can also suggest innovative technologies in the fields of precision farming and renewable energy for their significant role in the sustainability of dairy

farming in Pakistan and the challenges faced by small farmers in adopting such technologies.

Conflict of Interest

The authors declare no conflict of interest.

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