

TECHNICAL, ALLOCATIVE, AND ECONOMIC EFFICIENCY OF CAMEL MILK PRODUCTION AMONG PASTORAL HOUSEHOLDS IN ETHIOPIA: EVIDENCE FROM STOCHASTIC FRONTIER ANALYSIS

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Abstract

This study estimated the technical, allocative, and economic efficiency of camel milk production among pastoral households in the Shebelle Zone of the Somali Regional State, Ethiopia. Data were collected from 385 randomly selected camel milk-producing households using a structured questionnaire. Descriptive statistics and stochastic frontier analysis based on a Cobb-Douglas production function were used to estimate production efficiency and identify key determinants of camel milk yield per camel. The half-normal stochastic frontier model was statistically significant, and the likelihood-ratio test confirmed the presence of technical inefficiency. The results show high levels of efficiency among camel milk-producing households, with mean technical, economic, and allocative efficiency scores of 0.9679, 0.9677, and 0.9998, respectively. Milking frequency, health expenditure per camel, and supplementary feeding had positive and statistically significant effects on camel milk yield, whereas labor and pasture area had positive but not statistically significant effects. The findings show that modest gains in productivity and cost savings remain possible through improved milking management, animal health services, supplementary feeding, and pastoral extension support.

Keywords: camel milk, production efficiency, stochastic frontier, technical efficiency, allocative efficiency, economic efficiency.

JEL classification: Q12, Q18, D24, C21

1. Introduction

Camel milk sustains pastoral livelihoods in arid and semi-arid regions, where climate volatility and frequent droughts limit households' other income sources. In Ethiopia's Somali Regional State, Camels are a priority-reliant livestock. Providing milk, income, and nutrition during harsh conditions (Bekele Megersa et al., 2024). Unlike other ruminants, camels continue to lactate during long dry seasons, making camel milk essential for household consumption and market trade. Camel milk has attracted attention for its nutritional, therapeutic, and economic benefits. Camel milk is rich in vitamins, proteins, and bioactive compounds and remains an important food source for pastoralists. Commercialization of camel milk has accelerated due to urban demand, improvements in the market value chain, and the perception of camel milk as a premium product. Thus, the commercialization of camel milk is a key strategy to diversify income, reduce poverty, and strengthen food security for pastoralist communities. Despite its importance, camel milk production in pastoral settings is often characterized by low productivity, a limited market value chain, and weak institutional support.

Production primarily depends on traditional management practices, seasonal grazing, and the development of informal marketing value chains. (Bahta, M., Zemedu, & Gebremedhin, 2025; Bahta, S. et al., 2020; Battese & Coelli, 1995; Bekele Megersa et al., 2024)

These conditions raise important questions about the low efficiency of pastoral households using available resources and whether inefficiencies constrain the potential benefits of camel milk commercialization (Ait El Alia et al., 2025). Production efficiency in agriculture is commonly evaluated in terms of technical, allocative, and economic efficiency. Technical efficiency refers to the ability to produce maximum output from a given set of inputs. Allocative efficiency refers to the optimal use of inputs given their prices, and economic efficiency combines both dimensions, producing at the optimal output level for profit maximization (Ait El Alia et al., 2025; Greene, 2008). In pastoral livestock systems, inefficiencies often arise from limited veterinary services, inadequate feeding practices, and weak extension support.

This study assesses the technical, allocative, and economic efficiency of camel milk production of pastoral households in the Shebelle Zone of the Somali Regional State of Ethiopia through stochastic frontier analysis. It aims to quantify efficiency levels and pinpoint the principal determinants of camel milk production performance in pastoral settings, thereby furnishing a foundation for evidence-based policy interventions to boost the economic efficiency of camel milk production in these settings.

2. Literature Review and Theoretical Framework

Livestock production plays a central role in rural livelihoods in developing countries by contributing to food supply, income generation, employment, transport, social status, risk management, and household resilience. In pastoral and Agro-pastoral areas, livestock is not only an economic asset but also a major source of nutrition and livelihood security. The contribution of livestock is particularly important in arid and semi-arid areas where crop production is constrained by rainfall variability, recurrent drought, and limited access to productive resources. In such environments, camels are especially important because they can withstand heat stress, water scarcity, and seasonal feed shortages better than many other livestock species.

Camel milk production is increasingly recognized as a strategic livelihood activity in arid and semi-arid pastoral systems.

Camels can maintain milk production during dry seasons when cattle, goats, and sheep are more severely affected by feed and water shortages. This makes camel milk an important source of household nutrition, dietary diversity, and income among pastoral households. In the Horn of Africa, camel milk is also becoming increasingly commercially important due to rising urban demand, shifting consumer preferences, and its perceived nutritional and health benefits.

Recent studies show that camel milk contributes to household diets, supports income generation, and strengthens pastoral resilience, although the sector remains constrained by weak infrastructure, informal marketing systems, limited processing capacity, and poor cold-chain facilities (Elhadi et al., 2015; Gebremichael et al., 2019; Ho et al., 2022; Hassan et al., 2026).

In Ethiopia, camel production is closely associated with pastoral livelihoods, drought adaptation, mobility, and household food access. The Somali Regional State is one of the country's major camel-producing areas, and camel milk is an important commodity for both household consumption and local market exchange. However, camel milk production in pastoral systems remains largely extensive and traditional. Production depends heavily on seasonal grazing, household labor, animal health management, access to water, milking practices, and limited supplementary feeding. These conditions create productivity differences among households and raise important questions about how efficiently pastoral producers use available resources to produce camel milk.

Production efficiency in agriculture is commonly examined in terms of technical, allocative, and economic efficiency. Technical efficiency refers to the ability of producers to obtain the maximum possible output from a given set of inputs. Allocative efficiency refers to the ability to use inputs in cost-minimizing proportions, given input prices. Economic efficiency combines technical and allocative efficiency and reflects producers' ability to produce at minimum cost for a given output level. In livestock systems, efficiency may be influenced by management practices, animal health services, feed availability, labor allocation, access to extension, production technology, and market conditions (Battese & Coelli, 1995; Greene, 2008; Savickienė et al., 2025).

Stochastic frontier analysis is widely used to estimate agricultural production efficiency because it separates random shocks from one-sided inefficiency. This distinction is important in pastoral production systems, where milk output is affected not only by household management but also by drought, disease, feed availability, water access, climatic variability, and measurement errors. Unlike ordinary least squares models, stochastic frontier models allow deviations from the production frontier to be decomposed into random noise and inefficiency effects. This makes the approach suitable for assessing camel milk production efficiency under uncertain pastoral conditions (Battese & Coelli, 1995; Greene, 2008).

Previous livestock and dairy efficiency studies in Africa have largely focused on cattle dairy systems, crop-livestock farming, and smallholder mixed agriculture. These studies show that technical efficiency is often affected by feed use, animal health care, labor management, farm technology, market participation, and extension support. However, findings from cattle dairy systems cannot be directly generalized to camel milk systems because camels are managed under different ecological, biological, and institutional conditions. Camel milk production is often mobile, seasonally variable, and dependent

on rangeland dynamics rather than controlled farm-based feeding systems. Therefore, camel milk production requires context-specific efficiency analysis.

Studies on camel milk markets in Ethiopia and the Horn of Africa show that the sector has strong livelihood and commercial potential, but producers continue to face several constraints. These include limited veterinary services, poor milk handling practices, long distance to markets, weak transport systems, inadequate processing facilities, limited access to market information, and low bargaining power of producers. Such constraints reduce the benefits received by pastoral households and may limit productivity, commercialization, and income generation. Improving camel milk efficiency therefore requires both farm-level management improvements and value-chain support, including animal health services, supplementary feeding, milk collection centers, cooling facilities, market information, and pastoral-friendly credit services (Abduku et al., 2025; Hassan et al., 2026).

Although camel milk plays a central role in pastoral livelihoods, income generation, household nutrition, and resilience in arid and semi-arid areas, empirical evidence on the efficiency of camel milk production remains limited, particularly in Ethiopia's pastoral context. Existing livestock-efficiency studies have mainly focused on crop production, cattle dairy systems, and smallholder mixed farming, while camel milk production under mobile pastoral conditions has received limited empirical attention. Moreover, few studies have jointly estimated the technical, allocative, and economic efficiency of camel milk production while identifying the production inputs that explain differences in annual camel milk yield per camel. This creates an important knowledge gap for policy and development interventions in the Shebelle Zone, where camel milk is both a livelihood asset and a strategic food-security resource.

Conceptually, camel milk production efficiency in this study is understood as the relationship between production inputs, milk yield, production cost, and inefficiency. Milking frequency, labor input, health expenditure per camel, pasture area, and supplementary feeding are treated as key production inputs influencing annual camel milk yield per camel. Technical efficiency reflects the extent to which households produce the maximum possible milk yield from these inputs under existing production conditions. Economic efficiency reflects the ability of households to minimize production cost for a given level of output and input prices, while allocative efficiency reflects whether inputs are used in cost-minimizing proportions. The framework assumes that improved milking management, animal health care, feeding practices, and input allocation can move households closer to the production and cost frontiers.

Against this background, this study estimates the technical, allocative, and economic efficiency of camel milk production among pastoral households in the Shebelle Zone of the Somali Regional State, Ethiopia. By applying a Cobb-Douglas stochastic frontier production model and a stochastic cost-frontier approach, the study contributes empirical evidence on camel milk production efficiency and identifies practical areas for productivity improvement under pastoral production conditions.

3. Materials and Methods

3.1 Description of the Study Area

Shabelle is one of the eleven zones that comprise the Somali Region. This study was conducted in the Shebelle Zone of the Somali Regional State, located in eastern Ethiopia. The zone is bordered by Afdheer to the west, Fiq to the north, Korahe to the northeast, and Somalia to the south. It lies within a lowland

agro-ecological zone, with elevations ranging from about 250 to 600 m above sea level. The Shebelle River traverses the zone and plays a key role in sustaining pastoral and agro-pastoral livelihoods (FAO, 2022). Two primary rainy seasons occur: the Gu season (April–June) and the Dayr season (October–December). These seasonal rains largely determine livestock production patterns and grazing availability. The study area was deliberately selected because of its large camel population and its status as the main camel-milk production hub in the Somali Regional State. The Shebelle Zone relies heavily on camel-centric production methods; camel milk is a vital source of nutrition and economic benefit for pastoral households. The region also shows varying levels of market access and camel-milk commercialization, which influence the relationship among production efficiency, the value chain, and household well-being. The coexistence of traditional and emerging market-focused camel-milk value chains offers a suitable context for studying the factors that affect efficiency and commercialization in pastoral communities. The accessibility of the study sites and the availability of reliable data from local organizations further justified selecting this area for the research. The study focused on three major pastoral districts: Adaadle, Danan, and Godey. Addadle is characterized by extensive camel herds and year-round milk production supported by seasonal grazing and riverine pastures. Godey serves as one of the zone's administrative and commercial centers, where camel milk collection points and informal trading networks facilitate its marketing (FAO, 2018).

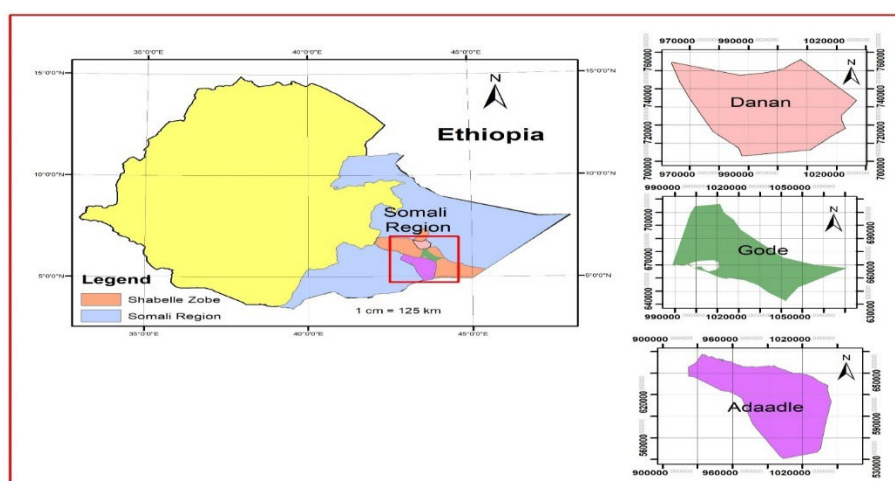


Figure 4. Map of the study area

Source: CSA Ethiopia (2021)

3.2. Research Design and Data Collection

The study used quantitative techniques. Quantitative data were collected through structured questionnaires to assess the efficiency of camel milk production and socioeconomic characteristics of pastoral households.

3.3. Population of study areas

The target population was households engaged in camel milk production in the Shebelle zone of the Somali region of Ethiopia. According to the 2007 census of Ethiopia conducted by the Central Statistical Agency, the total population of this zone is 464,253, of which 89,593 are urban, and 118,608 are pastoralists.

3.4. Sampling and sample size determination

A multistage sampling procedure was employed to select camel milk-producing households for the quantitative survey. In the first stage, three woredas of Shebelle Zone, namely Godey, Danan, and Adaadle, were purposively selected due to their high camel populations, the importance of camel milk production to pastoral livelihoods, and the presence of active camel milk marketing practices. In the second stage, nine kebeles were selected from the three woredas: Ilaan, Ceel-haar, and Hadhaawe from Godey woreda; Haardheer, Toon-fulan, and Garas-le from Danan woreda; and Dhurwaa-yale, Xananley, and Garas-madow from Adaadle woreda. In the final stage, camel milk-producing pastoral households were selected using systematic random sampling from household lists obtained from woreda livestock offices, kebele administrative records, and pastoral development structures.

The target population comprised households engaged in camel milk production in the Shebelle Zone. Although the 2007 Population and Housing Census reported 118,608 pastoral residents in the zone, this figure refers to individuals, not the exact number of eligible camel milk-producing households. Since a complete, up-to-date, zone-wide list of eligible camel milk-producing households was not available, the study used Cochran's sample-size determination formula for a large or unknown population. Assuming a 95% confidence level, a 5% margin of error, and a conservative population proportion of $p = 0.5$, the sample size was calculated as follows:

The sample size for a population proportion is calculated using formula 1:

$$n = \frac{Z^2 pq}{e^2} \quad (1)$$

Substituting $Z = 1.96$, $p = 0.5$, $q = 0.5$, and $e = 0.05$:

$$n = \frac{(1.96)^2 (0.5)(0.5)}{(0.05)^2} = 384.16 \approx 385 \quad (2)$$

where n is the required sample size, $Z = 1.96$ is the standard normal value at the 95% confidence level, $p = 0.5$ is the assumed population proportion, $q = 1 - p = 0.5$, and $e = 0.05$ is the margin of error.

Accordingly, 385 camel milk-producing households were included in the study.

The sample was distributed across the selected woredas as follows: 156 households from Godey, 125 households from Adaadle, and 104 households from Danan, representing 40.5%, 32.5%, and 27.0% of the total sample, respectively.

Table 1. Sample allocation by woreda

No.	Woreda	Allocated sample	Percentage (%)
1	Godey	156	40.5
2	Adaadle	125	32.5
3	Danan	104	27.0
	Total	385	100

Source: Authors' field survey data, 2025.

3.5 Methods of data collection

Primary and secondary data were used in this study; the primary data were collected through structured questionnaires administered to camel milk-producing households. The survey collected information on camel milk production, inputs used, and household socioeconomic characteristics. The questionnaires were validated by an agricultural economics expert and pre-tested for their reliability and validity. Secondary data were obtained from the government report and Somali regional statistical publications. Ethical clearance for this study was obtained from the College of Agriculture and Environmental Science Health

Research Ethics Committee of the University of South Africa, under reference number 2024/CAES_HREC/2691, prior to the commencement of data collection. All respondents were informed of the purpose of the study, and their participation was voluntary; they could withdraw at any stage without penalty or negative consequences.

3.6. Method of data analysis

Descriptive statistics were used to assess the demographic and socioeconomic characteristics of pastoral households' communities in the Shebelle zone of the Somali region of Ethiopia. These statistics provide a concise summary of the data and the interpretation of the respondents' main characteristics. Frequencies, means, percentages, proportions, and standard deviations were computed to describe the sample of households. The analysis was performed using the software (SPSS), Statistical Package for the Social Sciences (version 29), and Stata (version 17). The analysis also used stochastic frontier analysis using Cobb-Douglas production functions to estimate the efficiency and inefficiency of camel milk-producing households.

3.7. Model specification

The study applied a Cobb-Douglas stochastic production frontier model to estimate the technical efficiency of camel milk production. Annual camel milk yield per camel was used as the dependent variable. Total annual milk output was excluded from the explanatory variables because it is mechanically related to milk yield per camel and the number of lactating camels. The stochastic frontier production model was specified as formula 3:

$$\ln Y_i = \beta_0 + \beta_1 \ln MF_i + \beta_2 \ln LAB_i + \beta_3 \ln HE_i + \beta_4 \ln PA_i + \beta_5 \ln SF_i + v_i - u_i \quad (3)$$

where:

Y_i represents annual camel milk yield per camel for household i , measured in liters.

MF_i refers to milking frequency per day,

LAB_i represents labor input measured in person-days,

HE_i denotes health expenditure per camel in ETB,

PA_i represents pasture area measured in hectares,

SF_i refers to supplementary feed per camel measured in kilograms.

The term v_i is the symmetric random error term, assumed to be normally distributed as $v_i \sim N(0, \sigma_v^2)$, and captures random shocks beyond the control of the household. The term u_i is the non-negative technical inefficiency component, where $u_i \geq 0$, and is assumed to follow a half-normal distribution.

Technical efficiency was calculated by using formula 4:

$$TE_i = \exp(-u_i) \quad (4)$$

To estimate economic efficiency, a stochastic cost frontier was specified as follows:

$$\ln C_i^* = \alpha_0 + \alpha_1 \ln Y_i + \alpha_2 \ln W_{Li}^* + \alpha_3 \ln W_{Pi}^* + v_i + u_i \quad (5)$$

where C_i^* denotes the normalized production cost, Y_i denotes output, W_{Li}^* denotes the normalized labor price, and W_{Pi}^* denotes the normalized pastureland input price. In the cost frontier, v_i represents random noise, while u_i represents cost inefficiency.

Economic efficiency was calculated as follows:

$$EE_i = \exp(-u_i) \quad (6)$$

Allocative efficiency was then derived as the ratio of economic efficiency to technical efficiency:

$$AE_i = \frac{EE_i}{TE_i} \quad (7)$$

where TE_i , EE_i , and AE_i represent technical, economic, and allocative efficiency, respectively. All predicted efficiency scores were checked to ensure that they fell within the theoretical range of 0 to 1.

4. Results of the study

4.1. Demographic characteristics of the sampled households

The demographic results show that camel milk-producing households were male-headed, accounting for 70.4% of the sample, whereas female-headed households represented 29.6% (Table 2). Educational attainment was generally low, with 43.9% of household heads having no formal education and 31.4% having only primary education.

Table 2. Demographic characteristics of camel milk-producing households

Variable	Category	Frequency (n)	Percentage (%)
Education level	No formal education	169	43.9
	Primary education	121	31.4
	Secondary education	63	16.4
	Tertiary education	32	8.3
Sex of household head	Male	271	70.4
	Female	114	29.6
Place of residence	Pastoral	202	52.5
	Agro-pastoral	115	29.9
	Peri-urban	68	17.6

Source: Authors' computation from field survey data, 2025.

This shows that limited formal education may affect access to market information, adoption of improved camel husbandry practices, and interaction with formal institutions. Most respondents were

in pastoral areas, accounting for 52.5% of the sample, followed by agro-pastoral households at 29.9% and peri-urban households at 17.6%. This confirms that camel milk production in the study area remains predominantly rural and pastoral.

4.2 Descriptive statistics of camel milk production variables

The production statistics indicate considerable variation in camel milk production and input use among the 385 sampled households (Table 3). The average annual milk yield was 2,134.09 liters per camel, with yields ranging from 1,729.70 to 2,522.30 liters, indicating differences in productivity across households. Milking frequency averaged 1.97 times per day, while labor input averaged 179.57 person-days per year.

Table 3. Descriptive statistics of camel milk production variables

Variable	Mean	Std. dev.	Minimum	Maximum
Milk yield per camel per year (litters)	2,134.09	126.37	1,729.70	2,522.30
Milking frequency per day	1.97	0.66	1.00	3.06
Labour input (person-days/year)	179.57	61.78	14.65	361.10
Health expenditure per camel (ETB)	746.08	297.40	100.00	1,722.00
Pasture area (hectares)	12.66	6.14	1.00	31.25
Supplementary feed per camel/year (kg)	376.89	60.03	240.00	551.40
Total milk output per household/year (litters)	16,932.13	6,349.43	1,935.30	47,910.10
Number of lactating camels	2.33	0.96	1.00	5.00

Source: Authors' computation using Stata Version 17

Pasture expenditure, pasture area, and supplementary feed also varied widely, reflecting differences in animal health investment, grazing access, and feeding practices. Total household milk output averaged 16,932.13 litters per year, with a wide range from 1,935.30 to 47,910.10 litters, primarily due to differences in the number of lactating camels, herd management practices, and access to production resources.

4.3 Stochastic frontier analysis

The stochastic frontier production model was estimated using a Cobb–Douglas log-linear specification with annual camel milk yield per camel as the dependent variable (Table 4). The model assumes that deviations from the production frontier consist of two components: a symmetric random error term and a one-sided non-negative technical inefficiency term. The random error term captures statistical noise and external shocks beyond the control of pastoral households, while the inefficiency term captures household-level shortfalls from the attainable production frontier.

Table 4. Stochastic Frontier Production Model for Annual Camel Milk Yield per Camel

Model statistic	Result
Model	Normal/half-normal stochastic production frontier
Dependent variable	Annual camel milk yield per camel
Number of observations	385
Log likelihood	677.373
Wald $\chi^2(5)$	408.40
Prob > χ^2	<0.001

Model statistic	Result
LR test of $\sigma_u = 0$	chibar ² (01) = 3.67; p = 0.028

Source: Author's computation from household survey data, 2025

The model was estimated under the normal/half-normal distributional assumption, which is commonly applied in stochastic frontier analysis (Kumbhakar, Wang, & Horncastle, 2015). The Wald χ^2 value of 408.40 was statistically significant at the 1% level ($p < 0.001$), indicating that the selected production inputs jointly explained variation in annual camel milk yield per camel.

The likelihood-ratio test of $\sigma_u = 0$ was also significant (chibar² = 3.67; $p = 0.028$), confirming the presence of technical inefficiency and supporting the appropriateness of the stochastic frontier model.

Table 5 . Maximum Likelihood Estimates of the Cobb–Douglas Stochastic Frontier Production Function for Camel Milk Production

Variable	Coefficient	Std. error	z	p-value	95% confidence interval
ln Milking frequency	0.1084	0.0056	19.24	<0.001	0.0974 to 0.1195
ln Labor input	0.0055	0.0054	1.03	0.304	-0.0050 to 0.0161
ln Health expenditure	0.0096	0.0043	2.22	0.027	0.0011 to 0.0181
ln Pasture area	0.0040	0.0029	1.39	0.166	-0.0017 to 0.0096
ln Supplementary feed	0.0267	0.0130	2.05	0.040	0.0012 to 0.0521
Constant	7.3722	0.0855	86.21	<0.001	7.2046 to 7.5398
ln σ^2_v	-6.7875	0.1992	-34.08	<0.001	-7.1779 to -6.3971
ln σ^2_u	-6.3728	0.3762	-16.94	<0.001	-7.1102 to -5.6353
σ_v	0.0336	0.0033			0.0276 to 0.0408
σ_u	0.0413	0.0078			0.0286 to 0.0597
σ^2	0.0028	0.0005			0.0019 to 0.0038
$\lambda^\dagger$	1.2304	0.0107			1.2094 to 1.2515

Source: Author's computation from household survey data (2025)

The coefficient estimates show that milking frequency, health expenditure per camel, and supplementary feeding had positive and statistically significant effects on annual camel milk yield per camel. The coefficient for milking frequency was positive and significant at the 1% level, indicating that more frequent milking was associated with higher milk yield per camel.

Health expenditure per camel was also positive and significant, suggesting that investment in animal health services contributed to improved milk productivity. Similarly, supplementary feeding had a positive and statistically significant effect, showing that feed supplementation enhanced camel milk yield under pastoral production conditions. In contrast, labor input and pasture area had positive but statistically insignificant coefficients, indicating that their effects on milk yield were not strong enough to be statistically confirmed in the estimated model.

The estimated lambda value of 1.230 further indicates that variation in inefficiency exceeded random statistical noise in the production frontier.

This shows that improvements in household-level management practices, particularly camel milking management, animal health care, and supplementary feeding, could help pastoral households move closer to the estimated production frontier

4.4. Technical, economic, and allocative efficiency scores

4.4.1 Technical efficiency

The mean technical efficiency was 0.9679, indicating that camel milk-producing households achieved about 96.8% of their potential output under the existing technology and input-use conditions (Table 6).

Table 6. Summary statistics of technical, allocative, and economic efficiency

Efficiency measure	Mean	Std. dev.	Minimum	Maximum
Technical efficiency (TE)	0.9679	0.0148	0.8927	0.9913
Economic efficiency (EE)	0.9677	0.0148	0.8924	0.9913
Allocative efficiency (AE)	0.9998	0.0001	0.9997	1.0000

Source: Authors' computation using Stata Version 17

The remaining technical inefficiency gap was about 3.2%. This means that milk productivity could still be modestly improved through better camel milking management, animal health extension services, supplementary feeding, and improved production practices.

4.4.2 Economic efficiency

The mean economic efficiency was 0.9677, indicating that households were operating close to the estimated cost frontier. On average, households could reduce production costs by about 3.2% while retaining the same output level and input-price orientations.

4.4.3. Allocative efficiency

The mean allocative efficiency was 0.9998, indicating that households were almost fully allocatively efficient. This means that the input combinations were very close to the cost-minimizing allocation given the prevailing input prices. The tiny allocative inefficiency gap shows that the main remaining efficiency losses are more technical and economic than allocative.

4.5. Diagnostic tests

Diagnostic tests were conducted using a log-linear OLS model as a comparison model before estimating the stochastic frontier model. The OLS diagnostic model was statistically significant, $F(5,379) = 76.71$, $p < 0.001$, with $R^2 = 0.503$. The mean variance inflation factor (VIF) was 1.02, indicating no serious multicollinearity among the explanatory variables (Figure 2).

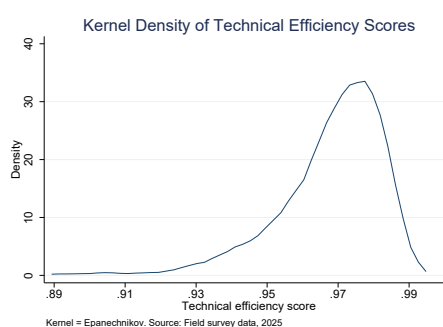


Figure 5. Technical efficiency score

Source: Authors' computation using Stata Version 17

The Breusch-Pagan/Cook-Weisberg test showed no evidence of heteroskedasticity, $\chi^2(1) = 0.01$, $p = 0.904$. The Shapiro-Wilk test did not reject the normality of the OLS residuals, $W = 0.993$, $p = 0.096$, although the skewness-kurtosis test indicated mild non-normality. The Ramsey RESET test and link test indicated possible functional-form limitations in the OLS diagnostic model. Therefore, the OLS model was used only for diagnostic comparison, while stochastic frontier analysis was retained as the main analytical model because the study's objective was to estimate efficiency relative to a production frontier. The likelihood-ratio test for the inefficiency component was significant, $\text{chibar}^2(01) = 3.67$, $p = 0.028$, confirming the presence of technical inefficiency and supporting the use of stochastic frontier analysis.

The kernel density distribution of technical efficiency scores shows that most camel milk-producing households are concentrated near the upper end of the efficiency range. The highest density occurs around 0.97–0.98, indicating that most households operated close to the estimated production frontier. The distribution has a small tail towards lower efficiency values, which means it is negatively skewed. This pattern suggests that while most households were technically efficient, some producers still operated below the main efficiency cluster. The result is consistent with the mean technical efficiency score of 0.9679, indicating that households achieved approximately 96.8% of their potential camel milk output under existing production conditions.

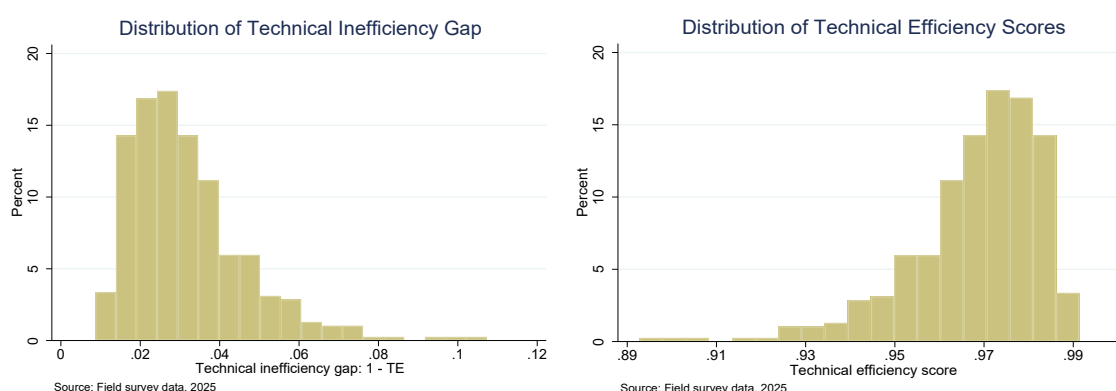


Figure 6. Technical inefficiency and technical efficiency distribution scores

Source: Authors' computation using Stata Version 17

The technical inefficiency gap, measured as $1 - TE$, represents the proportion of potential output lost due to technical inefficiency. The distribution is concentrated mainly between 0.01 and 0.05, indicating that most households lost only a small proportion of potential camel milk output. The highest concentration appears around 0.02–0.03, which is consistent with the average technical inefficiency gap of approximately 3.2%. Some households recorded larger inefficiency gaps, extending above 0.08, suggesting that targeted productivity support is still needed for relatively lower-performing producers. Overall, the figure confirms that technical inefficiency exists, but the average loss is modest.

The histogram of technical efficiency scores indicates that most camel milk producing households cluster near the upper end of the efficiency spectrum, between 0.96 and 0.99. This concentration shows that most households operate close to the estimated production frontier. A small tail extends towards lower efficiency values, implying that only a few households exhibit relatively lower technical efficiency.

The pattern is consistent with the mean technical efficiency score of 0.9679, indicating that households achieve roughly 96.8 % of their potential camel-milk output under current production conditions.

The residual average inefficiency of about 3.2 % indicates that modest productivity gains could still be achieved through improved milking management, animal health care, supplementary feeding, and better herd-management practices.

5. Discussion

This study provides empirical evidence on the technical, economic, and allocative efficiency of camel milk production among pastoral households in the Shebelle Zone of the Somali Regional State. The results show that households operated close to the production frontier, with a mean technical efficiency of 0.9679. This indicates that camel milk producers achieved about 96.8% of their potential output under existing input-use and production conditions. Therefore, the remaining technical inefficiency gap is modest, about 3.2%, rather than substantial. This finding shows that productivity improvements are still possible, but they are more likely to come from better management of existing resources than from large increases in herd size, pasture area, or labor use. This interpretation is consistent with recent efficiency studies that emphasize efficiency improvement as a practical pathway for increasing agricultural productivity where access to new technologies and production resources is limited (Tumuri, Geleta, & Sime, 2024)

The stochastic frontier results show that milking frequency, health expenditure per camel, and supplementary feeding were the significant determinants of camel milk yield per camel. These findings show the importance of production management, animal health care, and improved feeding practices in enhancing camel milk productivity. The positive and significant effect of milking frequency indicates that regular, appropriate milking practices contribute to higher milk yield. Similarly, the significance of health expenditure indicates that disease prevention, veterinary care, and animal health management are important for sustaining milk production. Supplementary feed also had a positive effect, confirming the role of improved feeding in supporting milk productivity, especially in pastoral areas affected by seasonal feed scarcity. Recent studies on camel production in Ethiopia also show that camel herders face climate variability, feed shortage, disease outbreaks, and water scarcity, which makes animal health and feeding management particularly important for maintaining production under arid and semiarid conditions (Gebremichael, Girmay, & Gebru, 2019).

Labor and pasture areas were positive but not statistically significant in the final model. This shows that simply increasing labour use or expanding grazing access may not automatically improve camel milk productivity unless accompanied by better herd management, animal health extension services, and improved feeding practices. This result is important for pastoral development policy because it indicates that efficiency gains should focus on the quality of management and access to services rather than solely on increasing the quantity of production inputs. Recent dairy and livestock efficiency studies similarly show that productivity differences are often related to management practices, technology use, feeding systems, and farm-level decision-making rather than input quantity alone (Savickienė, Namiotko, & Galnaitytė, 2025)

The economic efficiency result also shows that households were operating close to the cost frontier, with a mean economic efficiency of 0.9677. This implies that producers could reduce production costs by about 3.2% while maintaining the same output level under existing input-price conditions. Allocative

efficiency was very high, with a mean of 0.9998, indicating that households used input combinations that were nearly fully consistent with the cost-minimizing allocation under prevailing input prices. Therefore, the remaining efficiency gap appears to be more related to technical and cost-management improvements than to major input misallocation. This supports the use of a cost-frontier approach because economic efficiency depends not only on physical input use but also on input prices and cost-minimizing behaviour (Galata, Gemechu, & Zemedu, 2026)

The findings also have practical implications for camel milk development in the Shebelle Zone. Recent studies show that camel milk remains important for nutrition, income, and pastoral resilience in the Horn of Africa, while market access, infrastructure, milk handling, processing capacity, and value-chain organization remain major constraints (Abduku, Eshetu, Wolkaro, Berhe, & Jembere, 2025). Therefore, improving production efficiency should be linked with support for mobile veterinary services, disease prevention, dry-season feed availability, improved milking management, and pastoral extension services. Strengthening milk collection, handling, cooling, and market infrastructure may further increase the benefits of improved production efficiency. However, commercialization and food security outcomes should be interpreted as policy implications rather than direct causal findings of the SFA model because the empirical analysis in this article focused on production and cost efficiency.

Overall, the results indicate that camel milk-producing households in the study area operate at high efficiency levels, but modest productivity and cost-saving gains remain possible. The policy priority should therefore be to support lower-performing households and improve the practices that directly influence milk yield, especially animal health care, supplementary feeding, milking management, and extension support. These interventions can help producers move closer to the production frontier without increasing pressure on fragile rangelands.

6. Conclusions

The study assessed the technical, allocative, and economic efficiency of camel milk production among pastoralist households in the Shebelle Zone of the Somali Region, Ethiopia, using stochastic frontier analysis. The findings indicate that camel milk-producing households operate at the highest efficiency levels, with a mean technical value efficiency of 0.9679, mean economic efficiency of 0.9677, and mean allocative efficiency of 0.9998. These results show that households are close to both the production and cost frontiers, yet modest gains in productivity and cost savings are still attainable. The stochastic frontier analysis identified camel milking frequency, health expenditure per camel, and supplementary feeding as positive and statistically significant determinants of camel milk yields per camel. Labor input and pastureland area were positive but not statistically significant, implying that productivity gains are more likely to arise from improved camel milking management.

Animal health care, supplementary feeding, and extension services were more likely to increase productivity than increases in labour and pastureland area. A likelihood ratio test confirmed the presence of technical inefficiency, validating the use of stochastic frontier analysis. Diagnostic tests revealed no serious multicollinearity or heteroskedasticity; the Shapiro-Wilk test did not reject the normality of the OLS residuals. However, the RESET and link tests showed potential functional-form limitations in the OLS model, so the OLS results were used only for diagnostic comparison, while the stochastic frontier model remained the primary analytical tool. Policy interventions should focus on enhancing camel veterinary services, regular animal health Management, access to supplementary feed

during dry seasons, improved camel milking practices, and pastoral extension services. These measures can help lower-performing households approach the production frontier and boost camel milk productivity without adding pressure to fragile pastoral resources

6.1. Practical and policy implications

The findings have practical and policy implications for improving the efficiency of camel milk production and strengthening the camel milk value chain in the Somali Regional State of Ethiopia. First, the positive and significant effect of milking frequency indicates that productivity can be improved through better milking management. Pastoral extension services should therefore provide practical training on appropriate milking frequency, calf–milk sharing, hygienic milking, udder health, and milk handling.

Second, the significant effect of health expenditure per camel shows the importance of animal health services in improving camel milk yield. Regional and woreda livestock authorities should strengthen mobile veterinary services, vaccination, disease surveillance, and timely treatment in camel-producing kebeles, particularly in remote pastoral settlements where access to fixed clinics is limited. Third, the positive effect of supplementary feeding suggests that dry-season feed support is essential for improving camel milk productivity. Policy interventions should promote locally appropriate feed and fodder strategies, including rangeland rehabilitation, fodder banks, use of crop residues, water point management, and strategic supplementary feeding during dry seasons and drought periods.

Fourth, production-efficiency interventions should be linked with camel milk commercialization. Increasing milk yield alone will not improve household income unless producers have access to roads, milk collection points, hygienic containers, cooling facilities, storage, processing, transport services, credit, and reliable market information. Therefore, the Somali Regional State, woreda administrations, cooperatives, private investors, and development partners should adopt an integrated value-chain approach that combines productivity improvement with market access, pastoral finance, milk quality control, and price-stabilization mechanisms.

6.2. Limitations and future research

This study has some limitations that should be considered when interpreting the findings. First, the study used cross-sectional data collected from 385 camel milk-producing households in Godey, Danan, and Adaadle districts of the Shebelle Zone. Therefore, the results reflect production conditions during the survey period and may not fully capture seasonal and year-to-year changes in rainfall, feed availability, drought, disease outbreaks, and pastoral mobility.

Second, the study was limited to selected districts in one major camel-producing zone of the Somali Regional State. Although the Shebelle Zone is highly relevant to camel milk production, the findings should be generalized with caution to other pastoral areas of Ethiopia. Future studies should compare camel milk efficiency across different zones of the Somali Region and other pastoral regions, such as Afar and Oromia.

Third, the stochastic frontier model was estimated using a Cobb–Douglas functional form and a normal/half-normal inefficiency assumption. Although these assumptions are widely used in stochastic frontier analysis, future research should test the robustness of the results using alternative specifications, such as translog stochastic frontier models, truncated-normal inefficiency models, panel-data models, and Data Envelopment Analysis.

Finally, some relevant variables, such as camel breed, lactation stage, water access, disease history, milk quality, gender roles, climate shocks, and detailed input prices, were not fully captured. Future research should integrate production efficiency with camel milk commercialization, value-chain performance, household income, food security, and women's participation in milk marketing to provide stronger evidence for policy and program design.

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