A DEA-Based Sustainability and Efficiency Assessment of the Cashmere Supply Chain: From Tumurbulag Soum, Khuvsgul Province, Mongolia

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ABSTRACT

Mongolia is among the foremost producers of raw cashmere, a highly valued luxury fibre, yet its traditional supply chain is confronted with pressing issues of sustainability and efficiency. This study investigates the economic, social, and environmental dimensions of sustainability within the Mongolian cashmere supply chain, concentrating particularly on herder-level practices in Tumurbulag soum of Khuvsgul province. Data were gathered from 100 herder households through surveys, interviews, and field observations. The analysis employed Data Envelopment Analysis (DEA) using an input-oriented BCC model, with inputs comprising labour, feed, veterinary services, water and electricity, and equipment, while outputs included both the quantity of cashmere produced and the revenue generated. Findings indicate an average technical efficiency score of approximately 0.94 and a mean scale efficiency of 0.52, with 82 percent of households operating under increasing returns to scale. The greatest inefficiencies were associated with labour and feed, reflecting their frequent overuse relative to best-performing counterparts. Furthermore, many households displayed output shortfalls, particularly in terms of revenue, suggesting difficulties in capturing greater value from cashmere production. These results are examined through the lens of economic sustainability, which highlights low herder incomes and limited value capture, social sustainability, which reflects vulnerable livelihoods and demographic shifts in rural areas, and environmental sustainability, which is threatened by pasture degradation linked to expanding goat populations. The traditional Mongolian cashmere supply chain is therefore under considerable strain when assessed through the Triple Bottom Line (TBL) framework. Policy implications include the need to enhance herders' productive efficiency through training, cooperative structures, and improved resource utilisation, the strengthening of social protection and rural community development, and the adoption of sustainable grazing systems alongside supply chain traceability mechanisms. Strengthening both efficiency and sustainability is vital for safeguarding herder livelihoods, protecting fragile ecosystems, and maintaining the long-term viability of Mongolia's cashmere industry.

Keywords: Cashmere; Sustainable Supply Chain; Mongolia; Data Envelopment Analysis; Efficiency; Triple Bottom Line; Herders; Pasture Management

INTRODUCTION

Cashmere, often described as "soft gold," is an exceptionally fine and highly valued natural fibre distinguished by its softness, warmth, light weight, and durability (Lakshmanan, & Chakraborty, 2016). Derived from the undercoat of cashmere goats, it occupies a prominent position in the global luxury textile market (Franck, 2001). The international cashmere industry was estimated at approximately USD 3.5 billion in 2022, with forecasts suggesting growth beyond USD 5 billion by 2030, largely driven by rising demand for luxury garments (El País, 2024). In Mongolia, cashmere production plays a central role in the national economy, contributing around 5 percent of gross domestic product (GDP) and providing livelihoods for nearly 30 percent of the nomadic pastoral population (SwitchAsia, 2020). Goat herding for cashmere represents a key economic activity that sustains hundreds of thousands of rural households (United Nations Development Program, 2021). Consequently, the socio-economic conditions of rural communities are closely interlinked with the performance of the cashmere sector, highlighting its wider importance beyond luxury consumption (Morton et al., 2024; Zheng et al., 2023).

Khuvsgul Province is among Mongolia's principal cashmere-producing areas. In 2024, the province had a goat population of 1.895 million and produced 681.3 tons of raw fibre, ranking third nationally for herd size and fifth for cashmere output. Tumurbulag soum is particularly notable for the renowned "Erchmiin khar" breed, numbering 163,000 goats in 2024, recognised for producing superior quality cashmere (National Statistics Office of Mongolia, 2025). The soum is home to 4,278 residents across 998 herder households, representing about 4.5 percent of Khuvsgul's herders, with livestock production as their primary livelihood. Within this context, cashmere goats constitute the most important source of household income.

Sustainability challenges in the cashmere industry are closely linked to the structure of the traditional supply chain, which encompasses fibre procurement, processing, product transformation, and marketing (Ishrat et al., 2020; Ishrat et al., 2018). The foundational stage of herder-based production, shaped by difficult ecological and economic conditions, has a decisive influence on the overall sustainability of the supply chain (Tsogtbaatar et al., 2021; Wani et al., 2018). In pastoral economies such as Mongolia's, the efficiency and sustainability of this upstream segment are essential for the performance of the sector as a whole (Borza, 2014; Zhang et al., 2023). Despite this importance, the production stage remains comparatively underexplored in research, particularly in Mongolia, the world's second-largest supplier, even though it is critical to rural livelihoods and rangeland management (Morton et al., 2024).

The supply chain in Mongolia typically begins with herders combing goats during spring and selling raw fibre to traders or cooperatives (Morton et al., 2024). A substantial portion of this raw material is exported without further domestic processing, which limits the economic benefits captured by herders and local communities. This raise concerns over economic sustainability and fairness within the supply chain (Berger et al., 2013; Myagmarjav, 2021; Tsogtbaatar et al., 2021). Beyond these economic issues, environmental and social sustainability challenges are becoming increasingly evident. To cope with financial insecurity, herders have expanded their goat populations significantly (Berger et al., 2013). Over the past twelve years, livestock numbers have nearly doubled to 71.1 million, far exceeding the sustainable carrying capacity of rangelands (SwitchAsia, 2020; Wang et al., 2024). This rapid growth has caused widespread overgrazing and land degradation, threatening the long-term environmental viability of pastoral systems (Mearns, 2004). Socially, the expansion has deepened income inequalities, particularly affecting resource-poor herders with limited access to markets. Addressing these disparities is therefore central to achieving both social and environmental sustainability (Gombodorj, 2023; National Bureau of Statistics of China, n.d.).

Within this context, herder-level efficiency analysis becomes a critical entry point for advancing sustainability in the cashmere supply chain. Enhancing efficiency—achieving higher outputs with fewer inputs—can increase household income, reduce excessive resource use, and mitigate environmental degradation by easing grazing pressures (Danka et al., 2017; Islam et al., 2003; Wang & Feng, 2015). However, empirical studies assessing efficiency among Mongolian herders remain scarce. The present study addresses this gap by evaluating herder efficiency in a traditional cashmere-producing setting and linking the findings to wider sustainability considerations. The focus is on Tumurbulag soum in Khuvsgul province, a northern Mongolian district where pastoral nomadism and cashmere production remain central.

The study is guided by two primary questions: (1) what is the level and distribution of herder efficiency in converting inputs such as labour, feed, and costs into outputs such as cashmere fibre and revenue, and (2) how are inefficiencies connected to broader sustainability challenges within the supply chain? Tumurbulag soum was selected because it exemplifies traditional cashmere-producing communities. Local herders rely on practices such as manual combing, household-based labour, and indigenous rangeland management, while also engaging in newer developments, including increased commercial trade, cooperative participation, and the introduction of sustainability-oriented initiatives (Morton et al., 2024; Tugjamba et al., 2021). This mix of tradition and modernisation creates a valuable setting for studying efficiency and sustainability dynamics. Goat numbers in the soum have continued to grow, now exceeding half of the total livestock population (more than 300,000 head) (National Statistics Office of Mongolia, 2025). This expansion has intensified pressure on pastures, leading to visible land degradation, particularly near winter settlements. At the same time, the community faces social difficulties such as youth migration and limited infrastructure, which constrain access to markets and veterinary services, both of which are vital for herder efficiency.

To evaluate household-level efficiency in Tumurbulag, this research integrates quantitative and qualitative approaches through surveys and interviews. DEA is applied to benchmark herder performance against best-practice peers. This non-parametric method identifies gaps in efficiency, indicating where households could reduce inputs or increase outputs. The findings offer evidence on productivity and cost-effectiveness, which are critical to economic sustainability, while also exposing overuse of resources and revenue shortfalls that relate to environmental and social concerns. The subsequent sections outline the methodology, present efficiency scores alongside descriptive data, and explore their implications for advancing sustainable development in Mongolia's cashmere supply chain.

RESEARCH BACKGROUND

Sustainability refers to the capacity to preserve resources and systems over time, often conceptualised across economic, social, and environmental dimensions for both present and future generations (Glavič & Lukman, 2007; Kuhlman & Farrington, 2010; Vos, 2007). The Brundtland Commission defined sustainable development as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" A central framework for understanding sustainability is the TBL, introduced by Elkington in the 1990s, which emphasises economic viability, social equity, and environmental protection. The TBL has become a common reference point in industry and academic debates for evaluating sustainability (Elkington, 1997). Nevertheless, balancing these three pillars remains challenging, since economic priorities have historically dominated at the expense of environmental and social considerations (Eisenmenger et al., 2020). Achieving genuine sustainability requires integrated approaches that prevent long-term trade-offs between dimensions (Dernbach, 2003). Such integrated thinking is particularly significant in supply chains, which involve diverse stakeholders and shared resources (Cruz, 2008; Cruz & Matsypura, 2008; Handfield et al., 2005).

Supply chain efficiency denotes the capacity of a supply chain to use its resources effectively in delivering goods or services at the appropriate time, place, and quality while minimising costs and waste (Lichocik & Sadowski, 2013; Negi, 2020). Traditionally, efficiency involves meeting customer demand at the lowest possible total cost through streamlined processes, reduced excess inventories, and the removal of non-value-adding activities (Gunasekaran et al., 2004; Stevens, 1989). Performance measures can be categorised to show that resource utilisation indicators, such as costs and inventory levels, directly capture efficiency aspects in supply chain performance (Beamon, 1999). However, while efficiency remains important, it must be balanced with sustainability, a principle that is increasingly emphasised in Sustainable Supply Chain Management (SSCM) (Hervani et al., 2005; Wu & Pagell, 2010).

SSCM integrates sustainability principles into supply chain management by incorporating environmental, social, and economic considerations in a coordinated manner (Carter & Liane Easton, 2011). SSCM is described as managing material, information, and capital flows while considering objectives from all three dimensions of sustainable development, namely economic, environmental, and social (Seuring & Müller, 2008). Over the past two decades, SSCM has developed from its origins in green supply chain management, which primarily focused on environmental concerns, into a broader framework addressing all dimensions of the TBL (Carter & Liane Easton, 2011). Research highlights that SSCM not only enhances sustainability performance but also improves competitiveness and resilience across supply chains (Negri et al., 2021). Therefore, SSCM provides the conceptual foundation for examining how efficiency and sustainability can be pursued simultaneously, making it directly applicable to analysis of the cashmere supply chain.

Pastoral supply chains, which are based on extensive livestock systems, represent a complex intersection of efficiency and sustainability (Bernués et al., 2011; Borza, 2014). Efficiency aims include higher herd productivity, better logistics from remote regions, and improved processing capacity. Sustainability focuses on preserving rangeland ecosystems and safeguarding the livelihoods of pastoral communities (di Virgilio et al., 2019; Rapiya et al., 2025). In practice, these objectives can align improved herd management techniques, such as rotational grazing and rangeland restoration, can simultaneously increase yields and product quality, thereby enhancing income and efficiency without expanding herd sizes. This reduces environmental pressures while ensuring long-term pasture productivity (Smit et al., 2021). Reconciling efficiency and sustainability in such ecologically constrained systems requires innovative practices that respect natural limits but improve productivity through stronger knowledge and coordinated management (Ghisellini et al., 2016; Rehman & Farooq, 2023).

Pastoral and livestock-based supply chains face substantial TBL challenges, since they must reconcile economic, social, and environmental pressures (Dougherty et al., 2023; Singh & Srivastava, 2021). Environmentally, these include overgrazing, land degradation, biodiversity loss, and greenhouse gas emissions, particularly methane (Garnett et al., 2017; Lipson et al., 2019; Monteny et al., 2006; Shi et al., 2022). Climate change intensifies these threats by worsening extreme weather events, which accelerate pasture degradation and raise livestock mortality rates (Baumgard et al., 2012). Strategies such as improved grazing practices, rangeland restoration, and diversification of income sources are essential for mitigation (DeLonge & Basche, 2017; Ghahramani et al., 2019). From a social perspective, sustainability requires improving the living standards and preserving the cultural heritage of pastoral communities, who often face poverty, inadequate healthcare, limited access to education, and exclusion from market systems (Dyer, 2014; Muhammad et al., 2019; Zinsstag et al., 2016). Economically, volatility in markets for products such as cashmere undermines sustainable planning and incentivises short-term practices that damage the environment (Hatfield & Davies, 2006; Ishrat et al., 2018; Pahl, 2007). In addition, restricted access to finance and technology hinders productivity growth. Sustainable livestock supply chains therefore require an integrated approach, combining economic viability, environmental responsibility, and equitable social systems.

The cashmere supply chain illustrates how efficiency and sustainability interact in pastoral contexts. Cashmere, a luxury fibre obtained from goats, particularly those in high-altitude regions of Asia, is primarily produced in pastoral economies such as China, Mongolia, Iran, Afghanistan, and India (Ladakh and Kashmir) (Ansari-Renani, 2015; Ishrat et al., 2020; Morton et al., 2024; Waldron et al., 2014). The global cashmere sector exemplifies the tension between efficiency and sustainability in pastoral supply chains. China, the largest producer, has achieved efficiency by developing vertically integrated global value chains, enabling economies of scale through centralised production and processing (Waldron et al., 2014). However, this approach raises sustainability concerns, including rangeland degradation, displacement of pastoral livelihoods, and environmental impacts from industrial processing. By contrast, India's Kashmir pashmina sector reflects a traditionally sustainable, artisan-based system that now faces efficiency pressures (Ishrat et al., 2020). Mechanisation has increased output but undermines social sustainability by displacing artisans and weakening cultural traditions (Ishrat et al., 2020; Morton et al., 2024). Iran offers a further example where nomadic herders export raw cashmere efficiently but capture little added value due to a lack of domestic processing capacity, restricting economic sustainability (Ansari-Renani, 2015).

Taken together, these cases highlight the different ways countries balance efficiency and sustainability within cashmere production. They emphasise that efficiency alone cannot ensure long-term viability if ecosystems deteriorate or communities are marginalised, and that sustainability must incorporate efficiency to remain practical. These insights establish the foundation for identifying research gaps in the cashmere supply chain, which this study addresses in subsequent sections.

MATERIALS AND METHODS

Field Data Collection

A structured questionnaire survey was administered to 100 herder households, employing purposive sampling with the assistance of local authorities to ensure diversity in geographical representation and herd sizes. The survey collected demographic information, including household size, age, and education, as well as herd composition and management practices. It also recorded detailed input-output data relevant to cashmere production. The inputs comprised labour, feed expenditure, veterinary costs, water and energy use, and annualised equipment expenses, while the outputs included the quantity of cashmere produced (kilograms of raw fibre) and revenue generated from cashmere sales (Mongolian tugriks). In addition, the survey examined herders' perceptions of pasture conditions, herd productivity trends, involvement in cooperatives, and participation in training or support programmes, thereby offering essential contextual insights for analysing sustainability dynamics.

To complement the survey, primary qualitative data were collected using questionnaires, semi-structured interviews, observations, photographs, and documentary sources, enabling a comprehensive understanding of perspectives within the cashmere production sector. Interviews were conducted with stakeholders including Herders (H), Cooperatives (C), Middlemen (M), and Government officials (G), focusing on themes such as price volatility, gender roles in processing, the effects of youth migration, and environmental issues including pasture degradation and climate-related challenges. Each interview, lasting between 30 and 60 minutes, was recorded and analysed thematically. Furthermore, direct field observations at grazing areas, winter camps, and cashmere markets provided insights into pasture conditions, goat health, patterns of land degradation, market practices, and sustainable strategies such as rotational grazing and fodder cultivation. Summaries of the data collected from these varied sources and locations are presented in Table 1 and Table 2.

Table 1: Data Sources Collected from the Field Trip

Data		H	C	M	G
Type	Source				
Primary	Questionnaires	√			√
	Interviews	√	√	√	√
	Observation	√		√	
	Photograph	√	√	√	√

Table 2: Data Respondent Categories and Data Collection Source

Respondent Category	Data Source		
	Questionnaires	Interviews	Observation
Herders	100	10	10
Cooperatives		2	
Middleman（Change）		6	6
Government Officials		2	

Data Envelopment Analysis (DEA) Methodology

Each herder household was treated as a DMU. An input-oriented Banker-Charnes-Cooper (BCC) model under variable returns to scale (VRS) was applied, as herders generally exercise greater control over inputs such as labour and feed than over immediate output levels, and the model is appropriate for capturing differences in production scale among households (Banker et al., 1984; Charnes et al., 1978).

Let each herder j (j = 1,…,100) be represented by an input vector x_j and an output vector y_j.

$$x_j = (x_{1j}, x_{2j}, \dots, x_{5j})\ and\ y_j = (y_{1j}, y_{2j})$$

Where;

$$x_{1j} = Family\ Labour,$$

$$x_{2j} = Feed\ Expenditure,$$

$$x_{3j} = Veterinary\ Expenditure,$$

$$x_{4j} = Water/Electricity\ Costs,$$

$$x_{5j} = Equipment\ Costs,$$

$$y_{1j} = Raw\ Cashmere\ Quantity,$$

$$y_{2j} = Cashmere\ Revenue$$

The BCC DEA solves, for each decision-making unit (DMU) o, which means each herder household o, a linear program that minimizes a scalar:

$$\min_{\theta, \lambda_j} \theta$$

Subject to weighted sums of inputs and outputs meeting the constraints:

$$subject\ to \sum_{j=1}^{100} \lambda_j x_{ij} \leq \theta x_{io}\ , i = 1, \dots, 5\ ,$$

$$\sum_{j=1}^{100} \lambda_j y_{rj} \geq y_{ro}\ , r = 1,2\ ,$$

$$\sum_{j=1}^{100} \lambda_j = 1\ ,$$

$$\lambda_j \geq 0, \theta\ free$$

Using the VRS BCC model, overall efficiency was divided into technical efficiency (TE) and scale efficiency (SE). TE reflects the extent to which herders can transform inputs into outputs at their existing operational scale, while SE captures inefficiencies associated with herd size. In this study, TE was obtained from the VRS model, whereas overall efficiency (OE) was estimated through the constant returns to scale (CRS) CCR model. SE was then calculated as SE = OE / TE, where a value equal to 1 denotes that the household operates at an optimal scale, and a value below 1 indicates the presence of scale inefficiency.

Classification of returns to scale followed conventional DEA procedures. Specifically, when the BCC lambda coefficient equalled 1, the herder was considered to operate under constant returns to scale. A coefficient below 1 suggested increasing return to scale, implying that the herd was smaller than its optimal level and could increase outputs proportionally by expanding inputs. Conversely, a coefficient above 1 indicated decreasing returns to scale, meaning the herd size exceeded the optimal scale and would potentially benefit from input reduction. This interpretation directly corresponds to scale efficiency results: SE = 1 reflects an optimal scale, SE < 1 implies under-utilisation of scale (increasing returns), and SE > 1 signifies over-extension of scale (decreasing returns).

In addition to efficiency scores, the assessment also examined input and output slacks. Input slacks represent redundant input usage that could be further reduced after proportional efficiency adjustments without reducing output, whereas output slacks reflect potential additional output achievable without requiring extra inputs. These slack variables, denoted as S+ (input redundancies) and S− (output insufficiencies), were employed to identify specific inefficiency sources, such as excessive feed expenditure or inadequate cashmere yield relative to resource usage. Herders with TE = 1.000 and zero slacks were classified as strongly efficient, signifying Pareto-optimal performance. Those with TE = 1 but positive slacks were labelled as weakly efficient, denoting some inefficiency despite meeting proportional efficiency. Herders with TE < 1 were categorised as inefficient. The DEA calculations, including TE, SE, OE, slacks, and returns-to-scale classifications, were carried out using SPSSAU software, covering all 100 herder households included in the analysis.

Analysis of Sustainability Dimensions

In addition to efficiency measurement, the study incorporated both qualitative and supplementary quantitative data to assess sustainability across economic, social, and environmental dimensions. Survey responses and interview insights were systematically organised under the framework of the Triple Bottom Line. Economic sustainability was considered through indicators such as household cashmere income, diversification of revenue streams, financial constraints, and the distribution of value throughout the supply chain. Social sustainability was evaluated by examining aspects of community welfare, including intergenerational dynamics (for instance, whether younger members intended to continue herding), the role of gender in cashmere-related activities, and the extent of cooperative or collective practices. Environmental sustainability was assessed using observations of pasture quality, evidence of overgrazing, herders' experiences of climatic extremes such as droughts and dzud winters, and the application of sustainable land management techniques.

Qualitative interview material was thematically coded to identify recurring concerns reported by herders within each sustainability dimension, such as declining pasture quality, inequitable cashmere pricing, or youth migration. By triangulating DEA efficiency results with these sustainability indicators, the study sought to identify whether herders who achieved higher technical efficiency also demonstrated stronger economic performance and environmentally responsible practices, or whether tensions existed between efficiency and sustainability outcomes. For example, increasing input intensity to raise output may lead to improved efficiency in the short term but contribute to environmental degradation. Although the sample was confined to a single soum, the richness of the combined dataset offered scope for exploratory investigation of such relationships. The following section presents the findings in sequence, beginning with descriptive statistics, then outlining DEA efficiency scores, and concluding with an in-depth analysis of sustainability issues informed by both quantitative measures and qualitative evidence.

RESULTS AND DISCUSSION

Descriptive Analysis of Herder Households Survey Data

The survey of 100 herder households in Tumurbulag soum highlighted the traditional features of cashmere production, with the findings summarised in Table 3. On average, each household kept approximately 267 goats and produced about 105.4 kg of raw cashmere per year. This generated an average household revenue of ₮14.7 million (equivalent to $4100), although income levels varied considerably depending on herd size and breed quality. After accounting for mean input costs of ₮4 million, the average net income from cashmere sales amounted to ₮10.6 million ($2970). Based on the national income standard (National Bureau of Statistics of China, n.d.), the contribution of cashmere sales to the annual household income of the surveyed families was calculated at 21.06%. This figure only reflects earnings directly from cashmere sales, excluding income from mutton or other livestock-related sources. Despite its economic importance, this reliance exposes herders to risks associated with market fluctuations, reinforcing the crucial role of cashmere in sustaining local livelihoods.

Table 3. Results of the Herder Households Surveys

Overall Situation	Mean	Median	Range
Goats Number Per Household (Heads)	267	210	28-850
Number of Labour in Household	2.18	2	1-5
Total Input in Cash (₮)	4,048,500	3,297,500	350,000-14,000,000
Cashmere Produced Per Household(kg)	105.4	85	10-300
Selling Price of Cashmere (₮)	139,840	140,000	120,000-170,000
Net Income Brought by Cashmere (₮)	14,680,950	11,820,000	1,400,000-42,000,000

The pattern of input use among herder households was highly diverse. Household labour provided the backbone of production, averaging 2.18 adult full-time equivalents. In larger herding operations, additional workers were occasionally hired on a seasonal basis, with women most often engaged in cashmere combing, a task typically compensated at a daily rate of about ₮50,000 (USD 14). Expenditure on feed represented the most substantial financial commitment. On average, households spent ₮1.84 million (USD 515) annually on feed, which accounted for approximately 46% of their total input costs and highlighted a strong dependence on supplementary fodder (Figure 1). Only two households out of the 100 surveyed reported no feed purchase, indicating that nearly all relied on hay or fodder to maintain their goat herds.

The next most significant category of expenditure was related to equipment and fuel. All households possessed essential implements such as combs and shears, though many also utilised motorcycles or small trucks for herding tasks. Spending on this category averaged ₮1.14 million (USD 320) per household each year, comprising about 28% of total inputs.

Veterinary care followed as another notable expense, averaging ₮0.77 million (USD 215), largely devoted to vaccines and parasite treatments. Water and energy expenditures remained comparatively minor, except in cases where natural water sources were scarce. Taken together, the cost profile shows that feed consistently dominated household budgets, while equipment and veterinary services also absorbed considerable resources. These patterns carry direct implications for efficiency analysis: when substantial investments in feed, fuel, or animal health are not matched by equivalent increases in cashmere output, they will be reflected as technical inefficiencies.

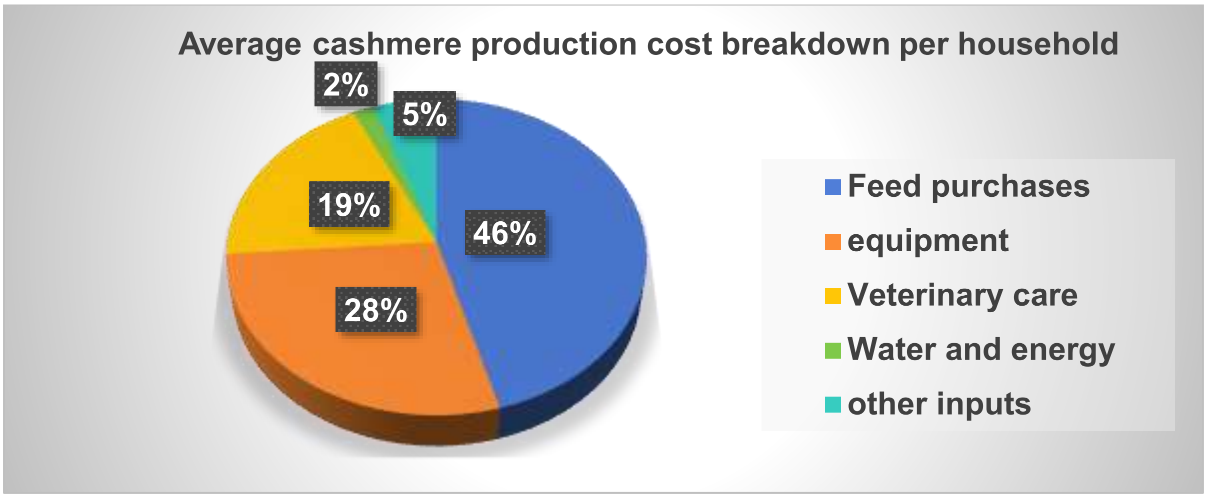

Figure 1. Average Cashmere Production Cost Breakdown Per Household

DEA Efficiency Analysis of Herders

The application of the input-oriented BCC DEA model to the sample of 100 herder households produced individual efficiency scores (Figure 2) and further revealed the presence of input and output slacks (Figure 3).

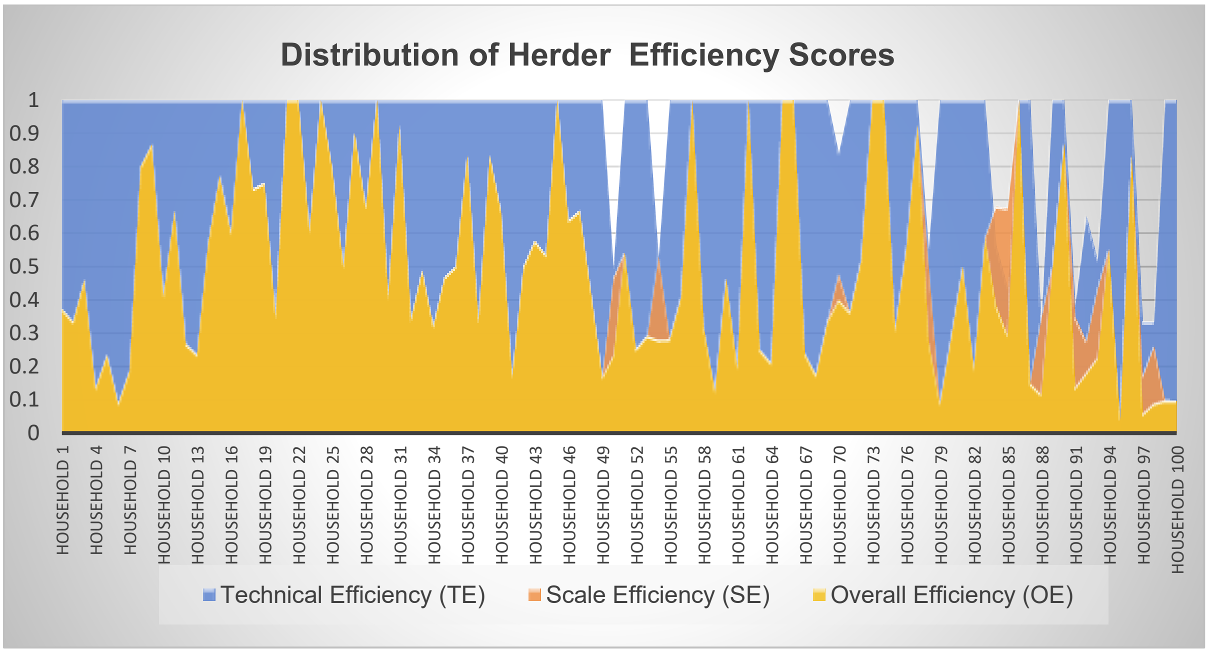

Figure 2. Distribution of Herder Efficiency Scores

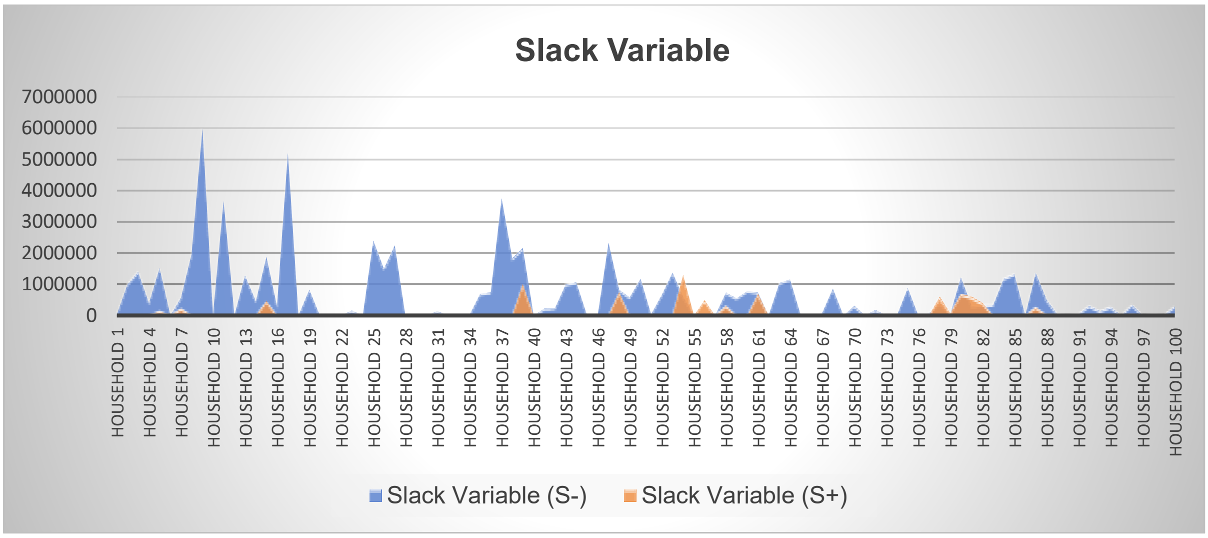

Figure 3. Slack Variables

The analysis of TE scores revealed a range from 0.333 to 1.000, with an overall mean of 0.940. Among the surveyed households, 88 achieved a score of 1.000, positioning them on the efficiency frontier, which indicates optimal use of inputs relative to outputs under DEA criteria. The remaining 12 households displayed varying levels of inefficiency. Approximately 88% of the sample recorded TE scores above 0.90, signalling near-efficient performance, while 1% fell within the 0.70–0.89 range and 11% scored below 0.70. The distribution shows that a single household with moderate efficiency (TE = 0.841) and 11 households with low efficiency (minimum = 0.333) account for the bulk of inefficiency within the sample. Although very small herds frequently failed to reach the efficiency frontier, inefficiencies were also observed among some medium- and large-sized herds, suggesting that management practices rather than herd scale primarily determine performance outcomes. The relationship between herd size and TE was weak and statistically insignificant ($|r| \approx 0.10$).

Under the CRS model, efficiency scores declined considerably, with average SE falling to 0.52. Only 13 households were found to operate under CRS, while 82% were characterised by Increasing Returns to Scale (IRS), indicating that their herd sizes remain below the technically optimal level. In contrast, 5% of households operated under Decreasing Returns to Scale (DRS), implying potential efficiency gains from reducing herd size (Figure 4). This distribution mirrors earlier patterns, but the lower mean SE highlights that scale-related inefficiencies are even more significant than initially identified.

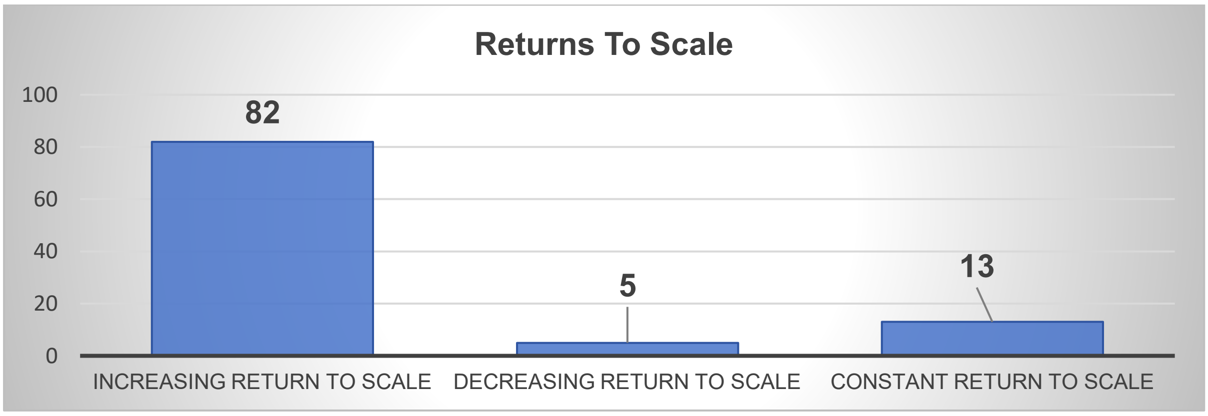

Figure 4. Returns to Scale

The examination of input slacks highlights considerable inefficiencies among the herders who did not attain full technical efficiency (TE < 1.0). Across this subgroup, redundant input use was evident in multiple categories. As indicated in Table 4, the most prominent excesses were found in water/electricity and miscellaneous expenses, each averaging nearly 22.2% of actual consumption, reflecting patterns of overuse or unnecessary spending. All 12 inefficient herders recorded redundancies in these areas, amounting on average to 76,977 ₮ and 291,038 ₮, respectively. Feed input also emerged as a critical area of concern, with mean slack estimated at 97,661 ₮, equivalent to 5.6% of feed applied, and observed in more than half of the inefficient households (7 of 12). This points to continuing difficulties in feed allocation and utilisation. Labour inefficiency, though less common, was present in three households, where an average surplus of 0.03 worker-equivalents (0.9% of total labour) suggested slight over-reliance on or underemployment of family members. In contrast, veterinary services showed no slack, implying either effective use or possibly even underutilisation. Redundancy in equipment inputs was minimal, averaging 38,889 ₮ (1.0%) and appearing in only one case, suggesting equipment-related inefficiency is marginal. Collectively, the slack analysis indicates that substantial efficiency gains could be realised through reducing costs in water/electricity, miscellaneous expenses, and especially feed, thereby improving the overall input efficiency of herder households.

Table 4. The Slacks of Input and Output

Input/Output Category	Average Slack (Absolute)	Average Slack (% of Observed)	Herders with Slack (Count)
Feed	97,661 ₮	5.60%	7
Labour	0.03 units	0.90%	3
Veterinary Care	0 ₮	0.00%	0
Water/Electricity	76,977 ₮	22.20%	12
Equipment	38,889 ₮	1.00%	1
Other Inputs	291,038 ₮	22.20%	12
Cashmere Quantity (kg)	0.72 kg	2.00%	4
Cashmere Revenue (₮)	159,833 ₮	2.10%	3

The output slack analysis revealed moderate but meaningful inefficiencies in both cashmere production and revenue among the herders who did not achieve full efficiency (Table 4). About physical production, around one-third of the inefficient households (4 out of 12) experienced an average shortfall of approximately 0.72 kg, representing about 2.0% of observed output. This indicates minor inefficiencies in production volume, which may be associated with herd health conditions, genetic characteristics of the goats, or environmental constraints. More significant, however, were the deficiencies recorded in cashmere revenue. Three of the inefficient households exhibited revenue shortfalls, averaging 159,833 ₮, equivalent to 2.1% of their actual revenue. This points to evident weaknesses in market performance and fibre quality management. The results suggest that, even when comparable quantities of cashmere are produced, certain herders fail to secure equivalent economic returns compared to their efficient counterparts. Such revenue inefficiencies are likely attributable to factors such as reduced price per kilogram, poorly timed market sales, or inadequate fibre sorting and quality control. Accordingly, strategies aimed at enhancing market access, developing better pricing mechanisms, and improving fibre quality management are as critical as input optimisation in closing efficiency gaps.

Taken together, the DEA findings illustrate several key points. First, overall efficiency has improved considerably, with 88% of households now operating on the VRS frontier, which reflects the recent diffusion of improved management practices. Nevertheless, scale inefficiencies continue to dominate, implying that policies promoting herd expansion or cooperative pooling could deliver additional productivity gains. Such initiatives, however, must be carefully aligned with the ecological limits of rangeland carrying capacity. Furthermore, targeted technical advice on feed budgeting and labour allocation would address the residual inefficiencies among the remaining households. Equally, improvements in fibre quality and enhanced market integration are essential for increasing cashmere revenues. Importantly, the achievement of these efficiency gains has the potential to raise household incomes and minimise resource wastage, thereby contributing to both economic and environmental sustainability. At the same time, it is necessary to consider whether the pursuit of efficiency may generate trade-offs for social and environmental outcomes. The following section therefore explores each dimension of sustainability in detail, integrating both the efficiency results and qualitative evidence.

Economic Sustainability Issues

Economic sustainability within the cashmere supply chain refers to maintaining stable earnings and economic resilience for all actors, particularly herders. In Tumurbulag, several constraints undermine this objective. The main issues include limited profitability and considerable income instability. For instance, the average household cashmere revenue of approximately $4100 (derived from 105.4 kg at $39/kg) accounts for only 21% of a family's annual subsistence costs. High production expenditures, especially for feed which commonly ranges between $1100 and $1200, further restrict net returns. Enhancing technical efficiency, particularly by reducing excess input use through improved herd management, represents a crucial pathway towards greater profitability and long-term sustainability.

Another pressing concern is the unequal distribution of power and value within the supply chain. Small and dispersed herders in Tumurbulag soum typically have limited capacity to negotiate favourable prices. They frequently sell at lower rates to mobile traders due to immediate financial needs or insufficient access to market information. As a result, downstream processors and international brands capture disproportionate profits, leaving producers economically exposed (Ishrat et al., 2020). Strengthening herders' position, for example through cooperative structures, establishing direct marketing channels that reward quality, and developing local processing capacity, could considerably stabilise household income. Even marginal price increases, such as 10%, could substantially raise livelihoods and strengthen overall economic sustainability.

Price volatility further undermines economic resilience. Cashmere values fluctuate in response to international demand and disruptions in trade, making incomes unpredictable and complicating long-term planning for herders. Respondents in Tumurbulag highlighted dramatic price declines during the Coronavirus disease 2019 (COVID-19) period, which exemplified these risks. Cyclical patterns of boom and contraction often drive herd expansion during favourable years, placing strain on rangelands, while sudden downturns leave households in financial distress. Although diversifying income streams can mitigate risk, genuine sustainability depends on balancing immediate productivity goals with long-term ecological limits, ensuring herd size is consistent with pasture capacity (Ishrat et al., 2020).

In practice, economic gains and sustainability improvements can reinforce one another. For example, reducing feed losses not only lowers expenses but also contributes to ecological stability by discouraging herd overgrowth. Similarly, rotational grazing enhances animal welfare and fibre quality, improving both market returns and environmental outcomes. Research on supply chain sustainability underscores these complementarities, noting that sustainable practices can simultaneously reduce costs and enhance brand reputation (Taghipour & Beneteau-Piet, 2020). With rising international demand for ethically and sustainably sourced cashmere, initiatives that link herders to responsible production programmes can provide price premiums. Expanding such schemes would create tangible economic incentives that align herders' profitability with sustainable production practices.

Social Sustainability Issues

Social sustainability within the cashmere value chain concerns the welfare, equity, and long-term resilience of the communities and individuals who participate in production, processing, and trade. In Tumurbulag soum, several social challenges are visible, particularly the strain on traditional pastoral lifestyles and rural social structures. One pressing issue is the declining appeal of herding among younger generations. Interviews suggested that many young people perceive herding as arduous and offering limited prospects and instead aspire to employment in urban areas. As one 22-year-old respondent expressed, while cashmere provides for basic needs, it does not offer a future. The household survey reinforced this observation: most household heads were over 50 years old, and relatively few families identified a younger successor willing to commit to herding. If such generational disengagement continues, there is a risk that vital knowledge—such as pasture stewardship and hand-combing methods—will not be passed on. Since herding in Mongolia is not merely an occupation but a cornerstone of cultural identity, this decline has social implications beyond economics, threatening the continuity of cultural heritage, family traditions, and the viability of rural communities.

Gender dynamics also represent an important dimension of social sustainability. In Tumurbulag, women perform a substantial share of cashmere-related tasks, particularly combing and sorting, yet decision-making authority typically rests with men, especially over marketing and household finances. This imbalance means that women's labour contributions are not always matched by direct benefits or decision-making power. Some female-headed households in the sample, especially widows or single women, reported greater autonomy in flock management, which enabled investments in children's education and household welfare. Expanding such empowerment opportunities could strengthen social outcomes. For example, targeted training for women in fibre grading (which directly affects price) or microfinance initiatives aimed at women's groups could enhance both economic and social equity. At the community level, questions of fairness and distribution also arise. Wealthier herders, with larger flocks, sometimes employ poorer neighbours, which can provide limited income redistribution. However, when cashmere prices fall or pastures degrade, even these informal support systems come under pressure, highlighting the fragility of social cohesion. Collective solutions, such as cooperative marketing, shared water use agreements, or community-based pasture management, have shown promise. In Tumurbulag, one herders' group that sells fibre collectively has reported stronger bargaining capacity and improved trust within the membership.

Cashmere's cyclical economic dynamics further intensify social stresses. During price booms, in-migrating herders seeking better grazing have occasionally triggered disputes with local households, whereas sharp downturns have left some families heavily indebted or forced out of herding altogether. One respondent recounted how a neighbour lost his entire herd in a dzud (a harsh winter disaster) and abandoned his camp, weakening the local community. These episodes illustrate how volatility in the cashmere market can erode community resilience. Building stronger adaptive capacity is therefore critical for social sustainability. Local institutions such as pasture user groups with enforceable collective rules, livestock insurance schemes, or mutual aid associations could help buffer communities against such shocks and preserve social cohesion.

The qualitative evidence highlighted three recurring themes: first, heritage and identity, with older herders strongly valuing their way of life yet uncertain about its continuation; second, equity and inclusion, with many respondents feeling that the benefits of cashmere trade are unevenly distributed—one herder remarked that "the trader in the Land Cruiser makes all the money," reflecting widespread perceptions of injustice; and third, well-being and future prospects, concerning whether families feel secure and optimistic about herding as a livelihood. On all three counts, scope for improvement remains. Initiatives grounded in sustainable supply chain principles could make important contributions. For instance, certification schemes for "fair cashmere" could integrate social criteria alongside environmental ones, requiring that a portion of premiums be reinvested in herder communities for schools, clinics, or other shared facilities. Such approaches would not only enhance livelihoods but also reinforce the cultural and social foundations on which Mongolia's pastoral economy depends.

Environmental Sustainability Issues

The environmental dimension of sustainability is perhaps the most critical in the Mongolian cashmere supply chain, since the very basis of production—the rangeland ecosystem—is increasingly under threat. In Tumurbulag, as in much of Mongolia, herders consistently described visible ecological decline: reduced grass availability, thinning plant cover, soil hardening, proliferation of unpalatable weeds, and early signs of desertification. Scientific assessments confirm these observations, estimating that approximately two-thirds of Mongolia's rangelands are already degraded or at high risk of degradation (Schmitz, 2016). The root driver is overstocking, particularly of goats. Unlike sheep, goats graze closer to the root, tearing vegetation and accelerating erosion. Rising international demand for cashmere has encouraged herd expansion, producing a feedback loop: declining pastures support fewer livestock, compelling households to enlarge herds to maintain income, which in turn intensifies the ecological damage. This dynamic is not merely a local concern but a nationwide sustainability crisis (Wang et al., 2024; Yan et al., 2023).

Findings from the DEA analysis reinforce this picture, revealing substantial redundancies in purchased feed inputs. While supplemental feeding can alleviate pasture pressure in the short term, feed itself ultimately derives from other grasslands, simply shifting the ecological burden rather than resolving it. Long-term sustainability depends on herd size management and a transition in production logic—from maximizing quantity to optimizing quality. Indeed, the most technically efficient households in the sample already maintained moderate herd sizes and reported practices such as selective breeding for higher-quality fibre and strategic destocking during drought years. These strategies allow them to sustain or even increase income while reducing grazing intensity. A system-wide pivot toward "fewer but better" animals could simultaneously improve herder livelihoods and relieve ecological stress, aligning with NGO-led initiatives currently piloted in Mongolia.

Beyond grazing, additional environmental stressors were identified. Water availability, though still relatively secure in Khuvsgul, is increasingly variable: households reported seasonal drying of springs, which they attributed to climate change and vegetation loss. This forces herders to drive animals longer distances to water, concentrating grazing near scarce water points and compounding pasture degradation. Climate variability adds another layer of vulnerability. Herders described more erratic rainfall, harsher summer droughts, and frequent dzud winters that decimate weakened herds. Pasture degradation and climate shocks interact in a vicious cycle: animals in poor condition due to degraded grazing are less resilient to dzud, while massive herd die-offs leave families destitute and rangelands even more stressed in recovery periods.

At the processing and downstream levels, Tumurbulag itself contributes minimally to industrial pollution, since large-scale washing and dyeing are concentrated in China. However, the global cashmere supply chain does carry a significant carbon and chemical footprint. Brands increasingly note these concerns, particularly regarding effluent discharge and transport emissions. Locally, herding systems are relatively low in fossil fuel inputs, which gives Mongolian production a comparative environmental advantage. Yet this advantage is fragile: if grasslands shift from carbon sinks to carbon sources through desertification, the net climate impact of cashmere could become highly negative. Some herders mentioned attempts to reseed pastures or plant windbreaks—practices promoted by land management programs—but adoption remains limited. Only about one in ten households had experimented with reseeding, with mixed outcomes due to low rainfall and the challenge of excluding free-ranging animals. Pilot initiatives such as rotational grazing, introduced through projects like the EBRD–SFA partnership, are still in early stages but offer potential pathways for wider adoption (Usov, 2023).

Ultimately, addressing the environmental sustainability of Mongolian cashmere requires a coordinated approach that extends beyond the household level. Herders alone cannot bear the costs of ecological stewardship in a highly competitive and volatile market. Institutional support—through government policy, donor programs, and supply chain actors—is essential. Mechanisms such as price premiums for fibre produced under verified sustainable grazing practices, subsidies for reseeding or fencing, or certification schemes rewarding moderate stocking rates could realign herders' incentives with ecological outcomes. Although Tumurbulag households had not yet encountered such programs, many expressed willingness to participate in cooperative arrangements that combine environmental responsibility with tangible economic benefit. Protecting rangelands is thus not only an ecological imperative but also a prerequisite for the long-term viability of both herding livelihoods and the global cashmere industry.

CONCLUSION AND POLICY RECOMMENDATIONS

For centuries, Mongolia's nomadic herders have sustained their livelihoods by producing some of the world's most prized cashmere, living in close connection with the cycles of nature. Today, this traditional supply chain is at a critical turning point. The case study conducted in

Tumurbulag soum, Khuvsgul province, highlights a complex interaction of efficiency gaps and sustainability pressures that must be resolved to ensure the sector's future. Based on these findings, several conclusions and policy-oriented recommendations can be drawn.

Efficiency and Economic Sustainability:

The DEA analysis revealed that many herders' functions below the efficiency frontier, pointing to considerable room for reducing resource wastage—particularly in the areas of feed and labour—while improving productivity. Raising efficiency directly translates into greater economic opportunity: achieving the same cashmere yield with fewer inputs would raise household income. To support this, policies should prioritize capacity-building for herders through training in herd nutrition (such as optimized feeding techniques that prevent overconsumption of fodder), animal health practices that enhance fibre production, and financial literacy to strengthen decision-making on input-output balances. Extension services can also promote peer-to-peer knowledge transfer, showcasing practices from more efficient herders to encourage wider adoption of innovation. These efficiency gains are not only economic but also consistent with broader sustainable supply chain goals, such as minimizing waste and maximizing resource effectiveness. Government and development actors are encouraged to design outreach initiatives in soums like Tumurbulag, including the development of exemplary "efficiency champions" who demonstrate profitable, resource-conscious herding. Parallel to this, strengthening herder cooperatives and improving their access to markets can significantly enhance economic resilience. Cooperatives enable members to achieve better selling prices through collective bargaining or direct processor contracts and allow cost savings through shared equipment and bulk feed procurement. Supportive policies—including formal legal recognition, leadership training, and small-scale financial support—would help cooperatives thrive. Ultimately, ensuring the economic sustainability of herding requires herders to capture a larger portion of the value chain. Expanding domestic value addition, such as investing in local dehairing or spinning facilities, would create new jobs in Mongolian communities and foster distinctive "Made in Mongolia" brands. This could be further reinforced by exploring labelling mechanisms such as fair trade or geographical indications to raise the international profile and premium value of sustainably produced Mongolian cashmere.

Social Sustainability and Community Well-Being:

Addressing social dimensions—including rural youth migration, gender inequities, and community resilience—requires an integrated strategy. Sustaining pastoral traditions depends on making herding a dignified livelihood with adequate social services. Investments are needed in education (such as mobile schools or better-equipped boarding schools to reassure families about children's prospects), healthcare (including routine medical and veterinary outreach to remote herders), and telecommunications infrastructure (expanding mobile network coverage to improve market access and emergency response). Cultural preservation also plays a role in social sustainability, for example through cashmere festivals, intergenerational training programs that blend traditional and modern herding techniques and ensuring platforms for women's participation in community decision-making. Women are critical contributors to the supply chain, and their empowerment—through microfinance, leadership positions in cooperatives, or support for small-scale entrepreneurial ventures such as handicraft production—can generate broad social and economic benefits. Partnerships between government and NGOs could strengthen women-led initiatives, providing alternative or supplementary income streams. Another essential measure is the creation or expansion of social safety nets. Given the recurrent risks posed by extreme weather and volatile markets, mechanisms like index-based livestock insurance can provide timely financial relief after harsh winters, preventing households from falling into poverty and helping sustain community cohesion. Furthermore, structured dialogue between herder groups and other supply chain actors—including processors, exporters, and policymakers—ensures that social factors, such as fair labour standards and community development, are embedded in broader sustainability strategies.

Environmental Sustainability and Resource Management:

Preserving the ecological foundation of the cashmere sector demands immediate action to address pasture degradation and adapt to changing climatic conditions. Scaling up community-led rangeland management is vital. This includes reintroducing governance structures for shared grazing land, with herder groups agreeing on stocking limits and seasonal rotation schedules. Government, with possible donor assistance, should provide technical assessments of carrying capacity and offer incentives such as ecosystem service payments for communities that adopt sustainable land practices. One viable option would be a pasture leasing scheme, granting herder groups long-term rights to specific areas on the condition of responsible management, thereby fostering stewardship rather than open-access exploitation. Diversifying feed resources is equally important—such as encouraging fodder crop cultivation, improving hay harvesting and storage, and utilizing crop residues—to ease pressure on natural pastures. The efficiency analysis indicates that feed is frequently underutilized; therefore, coordinated efforts to improve fodder self-sufficiency could reduce seasonal overdependence on fragile rangelands. Restoration measures must also be prioritized, including planting windbreaks, reseeding degraded pastures, and undertaking erosion control, potentially employing local labour as a form of livelihood diversification. Some herders have expressed willingness to reduce herd size if alternative income or compensation is available, suggesting voluntary destocking schemes may be feasible. Such programs could encourage households to keep fewer goats while diversifying into sheep or cattle, which offer additional income streams from wool and meat if linked to stronger markets. On a broader scale, sustainability standards should be embedded across the supply chain. Developing a Sustainable Cashmere Certification—incorporating indicators for pasture health and animal welfare, possibly monitored through remote sensing—could reward compliant herders with better prices and preferential market opportunities. Such a system would align environmental stewardship with economic incentives, while also responding to growing global demand for ethically sourced cashmere.

Integration and Multi-Stakeholder Collaboration:

The findings underscore that efficiency and sustainability issues are deeply interlinked and cannot be addressed in isolation. An integrated approach is necessary, and the establishment of a collaborative, multi-stakeholder platform is strongly recommended. Such a forum would bring together herder representatives, cooperatives, industry participants (processors and exporters), government bodies responsible for agriculture, environment, and social development, as well as NGOs and academic institutions. This structure would allow coordinated design and implementation of sustainability measures across the cashmere supply chain. Sharing experiences and data—such as insights from efficiency analysis or lessons from community-led practices—would improve collective decision-making. For instance, government rangeland policies could be aligned with industry purchasing strategies to incentivize adoption of sustainable practices among herders. Successfully managing a complex supply chain requires dialogue, collaboration, and acknowledgment of the diverse motivations of stakeholders. In Mongolia, a growing consensus is forming around the need to safeguard the long-term viability of the cashmere sector, a goal achievable only by simultaneously advancing environmental integrity, social well-being, and economic efficiency.

In conclusion, the cashmere supply chain in Tumurbulag and similar regions is at a defining crossroads. The evidence presents both a stark warning and an encouraging outlook. The warning is that unchecked resource depletion and persistent inequities risk pushing the system toward collapse—pastures could deteriorate beyond recovery, herders could abandon their traditional livelihoods, and an irreplaceable cultural legacy could vanish. Yet the hopeful message is that solutions already exist. The most efficient herders in the study demonstrate that careful resource management and innovation yield stronger outcomes, while cooperatives show that collective action can improve market terms. By scaling such successes and addressing remaining challenges through focused interventions, Mongolia can build a sustainable cashmere model—one that achieves efficiency in production, fairness in distribution, and ecological renewal. The path forward will demand effort from all actors—from herders adopting improved practices to policymakers enacting supportive reforms—but the rewards are profound: a resilient cashmere sector that sustains livelihoods, honours cultural traditions, and coexists harmoniously with Mongolia's iconic grasslands.

REFERENCES

Ansari-Renani, H. R. (2015). Cashmere production, harvesting, marketing and processing by nomads of Iran - A review. *Pastoralism*, *5*(1). https://doi.org/10.1186/s13570-015-0040-y

Banker, R. D., Charnes, A., & Cooper, W. W. (1984). Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis. *Management Science*, *30*(9), 1078-1092. https://doi.org/10.1287/mnsc.30.9.1078

Baumgard, L. H., Rhoads, R. P., Rhoads, M. L., Gabler, N. K., Ross, J. W., Keating, A. F., Boddicker, R. L., Lenka, S., & Sejian, V. (2012). Impact of Climate Change on Livestock Production. In *Environmental Stress and Amelioration in Livestock Production* (pp. 413-468): Springer Berlin Heidelberg. http://dx.doi.org/10.1007/978-3-642-29205-7_15

Beamon, B. M. (1999). Measuring supply chain performance. *International Journal of Operations & Production Management*, *19*(3), 275-292. https://doi.org/10.1108/01443579910249714

Berger, J., Buuveibaatar, B., & Mishra, C. (2013). Globalization of the Cashmere Market and the Decline of Large Mammals in Central Asia. *Conservation Biology*, *27*(4), 679-689. https://doi.org/10.1111/cobi.12100

Bernués, A., Ruiz, R., Olaizola, A., Villalba, D., & Casasús, I. (2011). Sustainability of pasture-based livestock farming systems in the European Mediterranean context: Synergies and trade-offs. *Livestock Science*, *139*(1-2), 44-57. https://doi.org/10.1016/j.livsci.2011.03.018

Borza, M. (2014). The Connection between Efficiency and Sustainability – A Theoretical Approach. *Procedia Economics and Finance*, *15*, 1355-1363. https://doi.org/10.1016/s2212-5671(14)00599-1

Carter, C. R., & Liane Easton, P. (2011). Sustainable supply chain management: evolution and future directions. *International Journal of Physical Distribution & Logistics Management*, *41*(1), 46-62. https://doi.org/10.1108/09600031111101420

Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research*, *2*(6), 429-444. https://doi.org/10.1016/0377-2217(78)90138-8

Commission on Environment and Development. (1987). Our common future (A/42/427). United Nations. https://digitallibrary.un.org/record/139811

Cruz, J. M. (2008). Dynamics of supply chain networks with corporate social responsibility through integrated environmental decision-making. *European Journal of Operational Research*, *184*(3), 1005-1031. https://doi.org/10.1016/j.ejor.2006.12.012

Cruz, J. M., & Matsypura, D. (2008). Supply chain networks with corporate social responsibility through integrated environmental decision-making. *International Journal of Production Research*, *47*(3), 621-648. https://doi.org/10.1080/00207540701513901

Danka, B., Grochowska, A., & van Rijt, K. (2017). *Influence Towards a Sustainable Cashmere Supply Chain: A Case Study of a Medium Sized Luxury Fashion Manufacturer in Scotland* [Master's Thesis, Blekinge Institute of Technology Karlskrona, Sweden]. https://d1wqtxts1xzle7.cloudfront.net/77420716/FULLTEXT02-libre.pdf

DeLonge, M., & Basche, A. (2017). Managing grazing lands to improve soils and promote climate change adaptation and mitigation: a global synthesis. *Renewable Agriculture and Food Systems*, *33*(3), 267-278. https://doi.org/10.1017/s1742170517000588

Dernbach, J. C. (2003). Achieving Sustainable Development: The Centrality and Multiple Facets of Integrated Decisionmaking. *Indiana Journal of Global Legal Studies*, *10*(1), 247. https://doi.org/10.2979/gls.2003.10.1.247

di Virgilio, A., Lambertucci, S. A., & Morales, J. M. (2019). Sustainable grazing management in rangelands: Over a century searching for a silver bullet. *Agriculture, Ecosystems & Environment*, *283*, 106561. https://doi.org/10.1016/j.agee.2019.05.020

Dougherty, J. C. H., Ridoutt, B., Jackson, M. K., Arsic, M., Juliano, P., & Oddy, V. H. (2023). A conceptual framework for modelling the role of livestock systems in sustainable diets and a sustainable planet. *Animal Production Science*, *63*(18), 1866-1886. https://doi.org/10.1071/an23300

Dyer, C. (2014). *Livelihoods and learning: Education for all and the marginalisation of mobile pastoralists*. Routledge. https://doi.org/10.4324/9780203083901

Eisenmenger, N., Pichler, M., Krenmayr, N., Noll, D., Plank, B., Schalmann, E., Wandl, M.-T., & Gingrich, S. (2020). The Sustainable Development Goals prioritize economic growth over sustainable resource use: a critical reflection on the SDGs from a socio-ecological perspective. *Sustainability Science*, *15*(4), 1101-1110. https://doi.org/10.1007/s11625-020-00813-x

El País. (2024). *Cashmere wars: how the elite fashion commodity is threatening Mongolia's ecosystem*. Retrieved 5 march from https://english.elpais.com/climate/2024-01-02/cashmere-wars-how-the-elite-fashion-commodity-is-threatening-mongolias-ecosystem.html

Elkington, J. (1997). The triple bottom line. In *Environmental management: Readings and cases* (Vol. 2, pp. 49-66). https://search.worldcat.org/title/1492325620

Franck, R. R. (2001). *Silk, mohair, cashmere and other luxury fibres* (Vol. 19). Woodhead Publishing. https://search.worldcat.org/title/1068930778

Garnett, T., Godde, C., Muller, A., Röös, E., Smith, P., Boer, I. J. M. d., Ermgassen, E. z., Herrero, M., Middelaar, C. E. v., Schader, C., & Zanten, H. H. E. v. (2017). *Grazed and confused? : Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question - and what it all means for greenhouse gas emissions*. https://edepot.wur.nl/427016

Ghahramani, A., Howden, S. M., del Prado, A., Thomas, D. T., Moore, A. D., Ji, B., & Ates, S. (2019). Climate Change Impact, Adaptation, and Mitigation in Temperate Grazing Systems: A Review. *Sustainability*, *11*(24), 7224. https://doi.org/10.3390/su11247224

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11-32. https://doi.org/10.1016/j.jclepro.2015.09.007

Glavič, P., & Lukman, R. (2007). Review of sustainability terms and their definitions. *Journal of Cleaner Production*, *15*(18), 1875-1885. https://doi.org/10.1016/j.jclepro.2006.12.006

Gombodorj, G. (2023). *Poverty, Sustainability and Livelihood Strategies of Herder Households in Mongolia* Debreceni Egyetem (Hungary)]. https://hdl.handle.net/2437/359271

Gunasekaran, A., Patel, C., & McGaughey, R. E. (2004). A framework for supply chain performance measurement. *International Journal of Production Economics*, *87*(3), 333-347. https://doi.org/10.1016/j.ijpe.2003.08.003

Handfield, R., Sroufe, R., & Walton, S. (2005). Integrating environmental management and supply chain strategies. *Business Strategy and the Environment*, *14*(1), 1-19. https://doi.org/10.1002/bse.422

Hatfield, R., & Davies, J. (2006). *Global review of the economics of pastoralism*. https://agritrop.cirad.fr/549237/1/document_549237.pdf

Hervani, A. A., Helms, M. M., & Sarkis, J. (2005). Performance measurement for green supply chain management. *Benchmarking: An International Journal*, *12*(4), 330-353. https://doi.org/10.1108/14635770510609015

Ishrat, S. I., Grigg, N. P., Bezuidenhout, C. N., & Jayamaha, N. P. (2020). Sustainability Issues in the Traditional Cashmere Supply Chain: Empirical Evidence from Kashmir, India. *Sustainability*, *12*(24), 10359. https://doi.org/10.3390/su122410359

Ishrat, S. I., Grigg, N. P., Jayamaha, N., & Pulakanam, V. (2018). Cashmere Industry: Value chains and sustainability. In *Sustainability in luxury fashion business* (pp. 113-132). Springer. https://doi.org/10.1007/978-981-10-8878-0_7

Islam, S. M. N., Munasinghe, M., & Clarke, M. (2003). Making long-term economic growth more sustainable: evaluating the costs and benefits. *Ecological Economics*, *47*(2), 149-166. https://doi.org/10.1016/S0921-8009(03)00162-9

Kuhlman, T., & Farrington, J. (2010). What is Sustainability? *Sustainability*, *2*(11), 3436-3448. https://doi.org/10.3390/su2113436

Lakshmanan, A., Jose, S., & Chakraborty, S. (2016). *Luxury hair fibers for fashion industry*. In S. S. Muthu & M. A. Gardetti (Eds.), *Sustainable fibres for fashion industry: Volume 1* (pp. 1–38). Springer Singapore. https://doi.org/10.1007/978-981-10-0522-0_1

Lichocik, G., & Sadowski, A. (2013). Efficiency of Supply Chain Management: Strategic and Operational Approach. *LogForum*, *9*(2). https://jbc.bj.uj.edu.pl/Content/936520/NDIGOC102679_9_2013.pdf#page=111

Lipson, J., Reynolds, T., & Anderson, C. L. (2019). Environmental implications of livestock series: goats. *Gates Open Res*, *3*(343), 343. https://doi.org/10.21955/gatesopenres.1115426.1

Mearns, R. (2004). Sustaining Livelihoods on Mongolia's Pastoral Commons: Insights from a Participatory Poverty Assessment. *Development and Change*, *35*(1), 107-139. https://doi.org/10.1111/j.1467-7660.2004.00345.x

Monteny, G.-J., Bannink, A., & Chadwick, D. (2006). Greenhouse gas abatement strategies for animal husbandry. *Agriculture, Ecosystems & Environment*, *112*(2-3), 163-170. https://doi.org/10.1016/j.agee.2005.08.015

Morton, J., Kotyza, P., Vigne, M., & Dashbaal, B. (2024). *Cashmere value chain analysis in Mongolia* [report](VCA4D CTR 2017/392-417).

https://agritrop.cirad.fr/611280/1/VCA4D.Mongolia.Cashmere.%202024.07.29.approved.V2.pdf

Muhammad, K., Mohammad, N., Abdullah, K., Mehmet, S., Ashfaq, A. K., & Wajid, R. (2019). Socio-political and ecological stresses on traditional pastoral systems: A review. *Journal of Geographical Sciences*, *29*(10), 1758-1770. https://doi.org/10.1007/s11442-019-1656-4

Myagmarjav, S. (2021). *Cashmere initiatives working together to improve the value chain*. United Nations Development Program. https://www.undp.org/mongolia/blog/cashmere-initiatives-working-together-improve-value-chain

National Bureau of Statistics of China. (n.d.). *National data*. Retrieved 23 March from https://data.stats.gov.cn/easyquery.htm?cn=C01

National Statistics Office of Mongolia. (n.d.). *Number of livestock, by type, by region, aimags and the capital* [Statistical table: DT_NSO_1001_109V1]. Retrieved September 4, 2025, from https://www.1212.mn/en/statcate/table-view/Regional%20development/Livestock/DT_NSO_1001_109V1.px

Negi, S. (2020). Supply chain efficiency framework to improve business performance in a competitive era. *Management Research Review*, *44*(3), 477-508. https://doi.org/10.1108/mrr-05-2020-0272

Negri, M., Cagno, E., Colicchia, C., & Sarkis, J. (2021). Integrating sustainability and resilience in the supply chain: A systematic literature review and a research agenda. *Business Strategy and the Environment*, *30*(7), 2858-2886. https://doi.org/10.1002/bse.2776

Pahl, L. I. (2007). Adoption of environmental assurance in pastoral industry supply chains - market failure and beyond. *Australian Journal of Experimental Agriculture*, *47*(3), 233. https://doi.org/10.1071/ea06031

Rapiya, M., Mndela, M., Truter, W., & Ramoelo, A. (2025). Assessing the Economic Viability of Sustainable Pasture and Rangeland Management Practices: A Review. *Agriculture*, *15*(7), 690. https://doi.org/10.3390/agriculture15070690

Rehman, A., & Farooq, M. (2023). Challenges, constraints, and opportunities in sustainable agriculture and environment. In *Sustainable Agriculture and the Environment* (pp. 487-501): Elsevier. http://dx.doi.org/10.1016/b978-0-323-90500-8.00012-9

Schmitz, R. (2016). *How Your Cashmere Sweater Is Decimating Mongolia's Grasslands*. National Public Radio. https://www.npr.org/sections/parallels/2016/12/09/504118819/how-your-cashmere-sweater-is-decimating-mongolias-grasslands

Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, *16*(15), 1699-1710. https://doi.org/10.1016/j.jclepro.2008.04.020

Shi, R., Irfan, M., Liu, G., Yang, X., & Su, X. (2022). Analysis of the Impact of Livestock Structure on Carbon Emissions of Animal Husbandry: A Sustainable Way to Improving Public Health and Green Environment. *Frontiers in Public Health*, *10*. https://doi.org/10.3389/fpubh.2022.835210

Singh, S., & Srivastava, S. K. (2021). Decision support framework for integrating triple bottom line (TBL) sustainability in agriculture supply chain. *Sustainability Accounting, Management and Policy Journal*, *13*(2), 387-413. https://doi.org/10.1108/sampj-07-2021-0264

Smit, H. P. J., Reinsch, T., Swanepoel, P. A., Loges, R., Kluß, C., & Taube, F. (2021). Environmental Impact of Rotationally Grazed Pastures at Different Management Intensities in South Africa. *Animals*, *11*(5), 1214. https://doi.org/10.3390/ani11051214

Stevens, G. C. (1989). Integrating the Supply Chain. *International Journal of Physical Distribution & Materials Management*, *19*(8), 3-8. https://doi.org/10.1108/eum0000000000329

SwitchAsia. (2020). *The True Cost of Cashmere*. https://www.switch-asia.eu/news/the-true-cost-of-cashmere/

Taghipour, A., & Beneteau-Piet, C. (2020). Sustainable Supply Chain Management Performance. *International Journal of Innovation, Management and Technology*, *11*(6), 165-169. https://doi.org/10.18178/ijimt.2020.11.6.897

Tsogtbaatar, S., Baival, B., Tsevelee, A., & Lkhamjav, O. (2021). *The Evaluations of the Code of Practice and Conformity Assessment for Pastureland in Herder Communities* Advances in Engineering Research, http://dx.doi.org/10.2991/aer.k.211029.013

Tugjamba, N., Walkerden, G., & Miller, F. (2021). Adaptation strategies of nomadic herders in northeast Mongolia: climate, globalisation and traditional knowledge. *Local Environment*, *26*(4), 411-430. https://doi.org/10.1080/13549839.2021.1891032

United Nations Development Program. (2021). *How sustainable cashmere is reversing land degradation in Mongolia*. https://www.undp.org/blog/how-sustainable-cashmere-reversing-land-degradation-mongolia

Usov, A. (2023). *EBRD supports sustainable cashmere production in Mongolia*. European Bank for Reconstruction and Development. https://www.ebrd.com/home/news-and-events/news/2023/ebrd-supports-sustainable-cashmere-production-in-mongolia.html

Vos, R. O. (2007). Defining sustainability: a conceptual orientation. *Journal of Chemical Technology & Biotechnology*, *82*(4), 334-339. https://doi.org/10.1002/jctb.1675

Waldron, S., Brown, C., & Komarek, A. M. (2014). The Chinese Cashmere Industry: A Global Value Chain Analysis. *Development Policy Review*, *32*(5), 589-610. https://doi.org/10.1111/dpr.12074

Wang, Q., Okadera, T., Nakayama, T., Batkhishig, O., & Bayarsaikhan, U. (2024). Estimation of the Carrying Capacity and Relative Stocking Density of Mongolian grasslands under various adaptation scenarios. *Science of The Total Environment*, *913*, 169772. https://doi.org/10.1016/j.scitotenv.2023.169772

Wang, Z., & Feng, C. (2015). A performance evaluation of the energy, environmental, and economic efficiency and productivity in China: An application of global data envelopment analysis. *Applied Energy*, *147*, 617-626. https://doi.org/10.1016/j.apenergy.2015.01.108

Wani, S. A., Shaheen, F. A., & Wani, M. H. (2018). Cashmere producing smallholder nomads of Himalaya: Survival challenges of a system. *Small Ruminant Research*, *163*, 45-50. https://doi.org/10.1016/j.smallrumres.2017.07.008

Wu, Z., & Pagell, M. (2010). Balancing priorities: Decision-making in sustainable supply chain management. *Journal of Operations Management*, *29*(6), 577-590. https://doi.org/10.1016/j.jom.2010.10.001

Yan, N., Zhu, W., Wu, B., Tuvdendorj, B., Chang, S., Mishigdorj, O., & Zhang, X. (2023). Assessment of the grassland carrying capacity for winter-spring period in Mongolia. *Ecological Indicators*, *146*, 109868. https://doi.org/10.1016/j.ecolind.2023.109868

Zhang, J., Wang, Y., Zhang, X., & Baoyindureng, B. (2023). Influence Mechanism of Green Supply Chain Interest Linkage of Grassland Livestock Products: A Study from the Perspective of Pastoral Modernization. *Sustainability*, *15*(15), 11830. https://doi.org/10.3390/su151511830

Zheng, W., Haifeng, X., & Min, Z. (2023). Development Status, Future Trends and Recommendations of China's Fine-Fibre Sheep Industry. *Special Report*, *59*(3), 300–315. https://doi.org/10.19556/j.0258-7033.20230306-04

Zinsstag, J., Bonfoh, B., Zinsstag, G., Crump, L., Alfaroukh, I. O., Abakar, M. F., Kasymbekov, J., Baljinnyam, Z., Liechti, K., Seid, M. A., & Schelling, E. (2016). A vision for the future of pastoralism. *Revue Scientifique et Technique de l'OIE*, *35*(2), 693-716. https://doi.org/10.20506/rst.35.2.2550