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Article

A Multidimensional Approach to the Sustainability Assessment of Dairy Farms in Grazing and Confinement Systems: Incorporating Animal Welfare as a Fourth Dimension of Sustainability

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Simple Summary

Dairy farming is essential for food production but faces growing challenges related to sustainability and animal welfare. This study evaluated 20 dairy farms in Chile, comparing two systems: grazing and confinement. Sustainability was assessed across four dimensions—economic, social, environmental, and animal welfare—using 58 practical indicators. Both systems reached high overall sustainability, and no significant differences were detected in global scores. Each system showed distinct strengths: confined farms performed better in productivity, manure management, and several social aspects, while grazing farms excelled in water and pasture management. Animal welfare results varied by indicator, underscoring the need to include welfare as a separate dimension in sustainability assessments. These findings suggest there is no single “best” system; rather, both systems can be sustainable when managed appropriately. The results can help farmers, policymakers, and consumers make informed decisions that support ethical, environmentally responsible, and socially fair dairy production.

Abstract

Dairy production is a fundamental component of the agricultural economy but faces increasing challenges regarding sustainability and animal welfare. Societal demand for ethical practices requires approaches that address environmental, economic, and social impacts without compromising animal well-being. This study assessed the sustainability of 20 dairy farms in southern Chile, classified as grazing or confinement systems, using 58 indicators grouped into four dimensions: economic, social, environmental, and animal welfare. Data was collected through structured sustainability surveys and on-farm welfare evaluations. Fisher’s exact test was applied to compare systems, revealing no statistically significant differences in overall sustainability ($p > 0.05$). Nevertheless, nine indicators showed significant variation between systems. Confined farms performed better in cow productivity, community engagement, diversification, cultural diversity, manure management, hind limb cleanliness, and shade availability. Grazing farms performed better in water resource management and grassland area. These results highlight the complexity of sustainability assessment and the need for multidimensional approaches that explicitly integrate animal welfare. Findings can inform system-specific strategies to improve sustainability in dairy production and guide policy development.

Keywords: sustainability assessment; dairy cattle; animal welfare; welfare ethics and policy; grazing systems; confinement systems

1. Introduction

In the ongoing effort to promote sustainable and ethical agricultural practices, the assessment of sustainability in dairy farms has emerged as a critically important area of interest in recent years [1–3]. Dairy production, whether in grazing or confined systems, plays a central role in food security and rural economies, yet faces persistent challenges related to environmental impact, animal welfare, and long-term system resilience [2,4–6]. Understanding the sustainability of different dairy production systems is therefore essential for developing strategies that support both productivity and responsible resource management.

Dairy farms commonly operate under two principal systems. Grazing systems meet most of the cows' nutritional requirements through pastures supplemented with conserved forages and concentrates, whereas confined systems house animals indoors and provide diets as total mixed rations [7,8]. Both systems have implemented various practices aimed at reducing environmental impacts, including nutrient management, manure handling, and efficient fertilization strategies [9–11]. However, their sustainability profiles differ. Grazing systems often exhibit a lower carbon footprint due to reduced reliance on external inputs and the carbon sequestration potential of pastures [9,12,13]. These systems may also promote biodiversity and soil health through more balanced ecological interactions [14], although their productivity can be constrained by climatic variability and forage availability [7].

Confined systems typically achieve higher productivity owing to precise dietary management and controlled environmental conditions [7,8,15]. Nonetheless, grazing systems may reduce expenses associated with animal health, as lower disease incidence and improved physical condition can decrease veterinary costs [16,17]. From an ecological standpoint, grazing systems often demonstrate advantages in water resource use and integration with natural landscapes [7,18], while confined operations may benefit from improved manure management infrastructure [13,19].

Social sustainability also varies between systems. Confined farms may promote more structured labor organization and worker interaction [17], whereas grazing systems offer closer contact with the natural environment but may present challenges related to employment stability and professional development [16]. Similar divergences are observed in animal welfare outcomes: confined systems can offer controlled housing conditions that enhance cleanliness and shade availability [20], while grazing systems allow animals to express more natural behaviors and may support improved overall welfare when well managed [19].

Despite these differences, most comparative studies on dairy sustainability have focused on environmental or economic aspects alone, with limited integration of social and animal welfare dimensions [7,8,16–23]. Given the strong interdependence between animal welfare, ecosystem health, productivity, and societal expectations, its inclusion as a fourth sustainability dimension is increasingly recognized as essential [2,3,22,24]. Improving animal welfare has been associated with benefits such as enhanced productivity, product quality, resource efficiency, and greater public acceptance of livestock production—the foundation of the “social license to operate” [22,25]. Incorporating welfare indicators into sustainability frameworks can support the identification of more effective management practices and promote higher standards across dairy systems [2,26–28].

In this context, there is a clear need for comprehensive assessment models that evaluate dairy sustainability while explicitly incorporating animal welfare. Therefore, the objective of this study was to assess the sustainability of grazing and confined dairy systems using a multidimensional model that includes animal welfare as a fourth dimension. The following sections describe the assessment model, its application to dairy farms in Chile, and the analysis conducted to determine the sustainability performance of the evaluated systems.

2. Materials and Methods

2.1. Study Period and Farm Selection

The study was conducted between July 2023 and April 2024 across the main dairy-producing regions of Chile. A total of 20 dairy farms were selected through convenience sampling, comprising ten grazing and ten confined farms. Each farm was visited once during the study period. During these visits, a structured sustainability questionnaire and an animal welfare assessment were administered to characterize the multidimensional sustainability of each production system.

2.2. Description of Dairy Production Systems

The general characteristics of the grazing and confined systems evaluated in this study are summarized in Table 1. These include differences in feeding strategies, housing, land use, herd size, and management practices.

Table 1. Summary of main characteristics of visited grazing (n = 10) and confined (n = 10) systems.

Variable	Grazing	Confined
Average number of cows milked	729	483
Average land area (ha)	603	510
Average milk production (lt/month)	571.61	704.87
Average milk production per cow per day (liters/cow/day)	21	38
Average productive life of cows	3.5	3.4
Predominant breed	Holstein	Holstein
Seasonality of births	January-March; July-September	Uniform throughout the year
Marketing of cull cows	Livestock fairs	Slaughterhouse
Feeding dairy cows	Pastures plus silage, including ryegrass, corn, chicory, oats, wheat, fodder cabbage, radish, and/or beet, and commercial concentrates during milking.	Stable ration based on concentrates and forages such as corn, alfalfa, oats, and/or barley husks, presented in the form of silage and hay.

2.3. Sustainability Assessment Model

The sustainability assessment tool was developed using indicators selected through a Delphi process with experts in sustainability and animal welfare, as described by Sánchez-Hidalgo and Tadich [29]. The tool comprised four sustainability dimensions—economic, social, environmental, and animal welfare—represented by 58 indicators: 12 economic, 14 social, 16 environmental, and 16 animal welfare indicators.

The evaluation consisted of three stages: (1) on-farm indicator data collection, (2) indicator scoring and data analysis, and (3) reporting of dimension-level and overall sustainability scores. Economic, social, and environmental indicators were obtained through structured questionnaires administered to farm owners or managers and to one employee per farm. Animal welfare indicators were assessed during milking and during the animals’ time on pasture, in pens, or in barns, following the recommendations of the Welfare Quality® protocol [30].

Consistent with prior methodological recommendations [2,5,31], specific indicators were omitted when valid information could not be collected or when measurement was not feasible. In

total, eight indicators were excluded due to data unavailability, absence of records, or logistical limitations:

- Economic dimension:
 - (1) *Income per liter of milk*, as economic viability already incorporated this measure;
 - (2) *Productive efficiency*, due to redundancy with cow, labor, and land productivity indicators;
 - (3) *Security and traceability*, due to the absence of traceability plans on all farms.
- Environmental dimension:
 - (4) *Greenhouse gas emissions*, as no farm had monitoring systems and measurement was not feasible;
 - (5) *Habitat conservation*, due to the impossibility of performing environmental sampling;
 - (6) *Air quality*, due to lack of monitoring equipment;
 - (7) *Carbon sequestration*, because soil sampling was not possible and values required estimation from national inventories [32];
 - (8) *Phosphorus balance*, as soil mineral analyses were unavailable for several farms.

2.4. Sustainability Scoring

Economic, social, and environmental indicators were scaled to a 0–1 range, where 0 indicated the absence of sustainability and 1 represented full sustainability. A relative scaling method was applied, using the best-performing farm as the maximum reference and the worst-performing farm as the minimum reference for each indicator, as adopted in previous sustainability assessment studies [19,21,33,34]. Animal welfare scores obtained through the Welfare Quality® protocol were originally expressed on a 0–100 scale and were normalized to a 0–1 range.

The cumulative sustainability percentage for each dimension was calculated using Equation (1):

$$\% I \text{ dimension} = \frac{N \text{ dimension}}{T \text{ dimension}} \times 100 \tag{1}$$

where *N* represents the number of indicators scored and *T* the total indicators in the dimension.

The overall sustainability score (IS) for each farm was calculated according to Equation (2):

$$IS = \frac{\%I \text{ dimension } 1 + \%I \text{ dimension } 2 + \%I \text{ dimension } 3 + \%I \text{ dimension } 4}{4} \tag{2}$$

This methodology follows the approach described by Meul et al. [19], Galioto et al. [2], Munyaneza [24], and Díaz de Otálora et al. [3]. All indicators were given equal weight, assuming equivalent relevance among dimensions.

2.5. Statistical Analysis

To compare sustainability levels between grazing and confined systems, Fisher’s exact test was applied due to the small sample size and the non-normal distribution of the data [35]. Indicators and dimensions were categorized into three sustainability levels based on their scaled scores: low (0.00–0.30), medium (0.31–0.60), and high (0.61–1.00), following Munyaneza [24]. Analyses were conducted in RStudio; significance was evaluated based on the distribution of sustainability levels between systems.

3. Results and Discussion

3.1. Sociodemographic Characteristics and Farm Continuity

Among the 20 producers interviewed, 85% (n = 17) had inherited their farms from family members, and 15% (n = 3) had acquired their farms independently. Inheritance confers access to physical assets (land, dairy cows, infrastructure, machinery) and intangible assets (accumulated knowledge, family tradition, experience, social networks), which can support continuity and long-term sustainability [36,37]. Producers ranged from 37 to 80 years (mean 58 years). The relatively high

mean age may pose a risk to continuity given the physical, emotional, and managerial demands of dairy farming [37–39]. Nevertheless, 80% (n = 16) of farms reported an identified successor actively engaged in management, whereas 20% (n = 4) lacked generational succession. In addition, 60% (n = 12) had defined action/improvement plans and community engagement activities, while 40% (n = 8) expected to cease operations within 10 years, citing prolonged droughts associated with climate change, urban expansion into rural zones, lack of generational continuity, and producer fatigue [37,39]. These factors should be considered within sustainability assessments due to their implications for risk management and long-term viability [40,41].

3.2. Describe Analysis of Sustainability Indices

Table 2 summarizes the sustainability scores for each dimension—economic, social, environmental, and animal welfare—as well as the Global Sustainability Index (GSI) and sustainability level for grazing and confined dairy systems. Confined systems exhibited higher mean scores in the economic (0.74), social (0.86), and environmental (0.58) dimensions, whereas grazing systems obtained a higher score in animal welfare (0.69). The GSI was slightly higher for confined farms (0.71) than for grazing farms (0.66); however, both systems achieved a high overall sustainability level.

Table 2. Sustainability Index score obtained for dimension economic social, environmental and animal welfare dimension achieved by grazing and confined dairy systems.

System	IS				GSI	Level
	Economic	Social	Environmental	Animal welfare		
Grazing	0.69	0.72	0.54	0.69	0.66	High
Confined	0.74	0.86	0.58	0.67	0.71	High

These results align with reports of higher economic performance and management control in confined systems and with advantages in animal-oriented practices in grazing farms settings [2,3,19].

Despite differences in mean sustainability scores, no statistically significant differences were identified between grazing and confined systems for any dimension or for the GSI (p > 0.05; Table 3). Thus, the initial hypothesis of higher overall sustainability in grazing systems was not supported. Comparable findings have been reported in prior assessments where structural differences did not translate into significant contrasts in overall sustainability outcomes [18,19,21].

Table 3. Proportion of dairy farms by sustainability levels and dimension in grazing and confined dairy systems.

Dimension	Grazing			Confined			p-value
	Low	Medium	High	Low	Medium	High	
Economic	0.0	0.2	0.8	0.0	0.2	0.8	1.0
Social	0.0	0.2	0.8	0.0	0.0	1.0	0.5
Environmental	0.0	0.7	0.3	0.1	0.2	0.7	0.1
Animal welfare	0.0	0.2	0.8	0.0	0.4	0.6	0.3
Global	0.0	0.2	0.8	0.0	0.0	1.0	0.5

3.3. Indicator-Level Analysis by Sustainability Dimension

3.3.1. Economic Dimension

Within the economic dimension, the indicator “cow productivity” differed significantly between systems (p = 0.003), with higher productivity levels observed in confined systems (Table 4). This aligns with literature indicating that confined systems benefit from greater control over diet

formulation, feeding consistency, and environmental conditions, supporting higher and more stable milk yields [15,20,42]. Although grazing systems may reduce veterinary, breeding, and medication costs due to improved animal health and longevity [16,17], their reliance on climate and forage availability can constrain productive potential, particularly in high-genetic-merit dairy cows [43].

Table 4. Proportion of dairy farms and p-value by indicators for each dimension and levels in grazing and confined dairy systems.

Dimension	Indicator	Grazing			Confined			p-value
		Low	Medium	High	Low	Medium	High	
Economic	Viability	0.5	0.1	0.4	0.4	0.1	0.5	0.80
	Cow productivity	0.4	0.3	0.3	0.0	0.0	1.0	<0,05
	Labor productivity	0.8	0.1	0.1	0.6	0.3	0.1	0.62
	Feed conservation	0.0	0.0	1.0	0.0	0.0	1.0	1.00
	Animal disease control	0.0	0.0	1.0	0.0	0.0	1.0	1.00
	Breeding system	0.0	0.0	1.0	0.0	0.0	1.0	1.00
	Forage self-sufficiency	0.5	0.0	0.5	0.5	0.0	0.5	1.00
	Profitability	0.0	0.0	1.0	0.0	0.0	1.0	1.00
	PIB contribution	0.7	0.2	0.1	0.7	0.1	0.2	1.00
	Financial autonomy	0.2	0.0	0.8	0.3	0.0	0.7	0.63
	Transmissibility	0.2	0.0	0.8	0.2	0.0	0.8	1.00
	Land productivity	0.0	0.0	1.0	0.0	0.0	1.0	1.00
Social	Level of schooling	0.0	0.0	1.0	0.2	0.0	0.8	0.47
	Level of training	0.1	0.0	0.9	0.1	0.0	0.9	1.00
	Community engagement	0.6	0.0	0.4	0.0	0.0	1.0	0.01
	Generational transition	0.4	0.0	0.6	0.3	0.0	0.7	1.00
	Risk of abandonment	0.3	0.0	0.7	0.6	0.0	0.4	0.36
	Work satisfaction	0.1	0.0	0.9	0.0	0.0	1.0	1.00
	Economic dependence	0.0	0.0	1.0	0.0	0.0	1.0	1.00
	Work intensity	0.5	0.0	0.5	0.4	0.0	0.6	0.64
	Quality of life	0.0	0.0	1.0	0.0	0.0	1.0	1.00
	Collective work	0.2	0.0	0.8	0.0	0.0	1.0	0.47
	Hygiene and safety	0.0	0.0	1.0	0.0	0.0	1.0	1.00
	Diversification of activities	0.8	0.0	0.2	0.1	0.0	0.9	<0,05
	Labor rights	0.0	0.0	1.0	0.0	0.0	1.0	1.00
	Cultural diversity	0.7	0.0	0.3	0.0	0.0	1.0	<0,05

Environmental	Soil resource management	0.5	0.0	0.5	0.1	0.0	0.9	0.14
	Water resource management	0.0	0.0	1.0	0.5	0.0	0.5	<0,05
	Water quality	0.7	0.0	0.3	0.6	0.0	0.4	1.00
	Space valorization	0.4	0.0	0.6	0.1	0.0	0.9	0.30
	Specialization	0.1	0.8	0.1	0.3	0.7	0	0.58
	Crop biodiversity	0.1	0.8	0.1	0.4	0.4	0.2	0.22
	Animal biodiversity	0.3	0.0	0.7	0.3	0.0	0.7	1.00
	Crop rotation	0.3	0.0	0.7	0.3	0.0	0.7	1.00
	Grassland area	0.0	0.0	1.0	0.8	0.0	0.2	<0,05
	Organic waste management	0.4	0.0	0.6	0.1	0.0	0.9	0.30
	Fertilization	0.0	0.0	1.0	0	0.0	1.0	1.00
	Manure management	0.9	0.0	0.1	0.1	0.0	0.9	<0,05
	Pesticide use	0.8	0.0	0.2	1.0	0.0	0.0	0.47
	Energy efficiency	0.3	0.0	0.7	0	0.0	1.0	0.21
	Disposal of milk from animals that received medication	0.6	0.0	0.4	0.3	0.0	0.7	0.16
	Greenhouse gas production	0.1	0.2	0.7	0.1	0.1	0.8	1.00
Animal Welfare	Body condition	0.9	0.1	0.0	1.0	0.0	0.0	1.00
	Access to water	0.1	0.0	0.9	0.0	0.0	1.0	1.00
	Dimension of milking stalls	0.1	0.0	0.9	0.2	0.0	0.8	1.00
	Floor condition	0.0	0.0	1.0	0.0	0.0	1.0	1.00
	Cleanliness score of udders	0.0	0.1	0.9	0.3	0.2	0.5	0.17
	Cleanliness score of hindquarters	0.8	0.2	0.0	0.5	0.0	0.5	0.04
	Condition of holding pen floor	0.0	0.0	1.0	0.0	0.0	1.0	1.00
	Presence of shade	0.7	0.0	0.3	0.0	0.0	1.0	<0,05
	Teat condition score	0.3	0.0	0.7	0.3	0.0	0.7	1.00
	Absence of cow with tail injuries	0.3	0.0	0.7	0.5	0.0	0.5	0.36
	Locomotion score	0.7	0.3	0.0	0.7	0.2	0.1	1.00
	Use of analgesics and anesthetics	0.1	0.2	0.9	0.0	0.0	1.0	0.48

	in painful procedures							
	Pain management in acute illness	0.1	0.0	0.9	0.1	0.0	0.9	1.00
	Expression of positive social behaviors	0.2	0.0	0.8	0.3	0.0	0.7	0.62
	Flight zone distance	0.2	0.0	0.8	0.3	0.0	0.7	0.62
	Quality and cleanliness of drinking troughs	0.3	0.0	0.7	0.7	0.0	0.3	0.07

3.3.2. Social Dimension

Significant differences were observed for community engagement ($p = 0.01$), diversification ($p = 0.005$), and cultural diversity ($p = 0.003$), with confined farms showing higher sustainability levels (Table 4). Given the scarcity of direct comparisons of social indicators between dairy systems, these results are noteworthy. Social sustainability has gained importance in response to evolving consumer expectations and labor conditions; including social indicators can improve decision-making processes, traceability, and working conditions for farmers and employees [37,40,41,44,45].

3.3.3. Environmental Dimension

Within the environmental dimension, water resource management ($p = 0.01$) and pasture area ($p = 0.0007$), favored grazing systems, whereas manure management ($p = 0.00002$) favored confined systems (Table 4). Prior studies have reported lower eutrophication potential and ammonia emissions in grazing systems, though higher global warming impacts have also been documented in some contexts [8,26]. In this study, superior manure management in confined systems may reflect infrastructural capacity and controlled handling practices. Environmental sustainability assessments support practices that optimize feed use, reduce nutrient losses, and minimize emissions to soil, water, and air [26,44,45].

3.3.4. Animal Welfare Dimension

For animal welfare dimension, hind limb cleanliness ($p = 0.04$) and shade availability ($p = 0.003$) were higher in confined systems (Table 4). These results suggest that controlled housing conditions and targeted infrastructure can improve specific indicators. Despite close links with economic, environmental, and social dimensions, animal welfare remains underrepresented in sustainability assessments [2,22,46]. Incorporating animal welfare as an independent dimension within sustainability frameworks is essential, particularly given public concern for sustainable dairy farming and product quality [5,47].

3.3. Limitations and Implications

The absence of significant differences in overall sustainability may reflect the limited sample size and the application of relative scaling, which standardize scores within the study population [8,19]. Data availability constraints and limited record-keeping, particularly for economic and environmental variables, may also have influenced indicator accuracy. Accordingly, sustainability scores should be interpreted relatively within this population rather than as absolute benchmarks.

5. Conclusions

This study provides an integrated sustainability assessment of dairy farms that explicitly incorporates animal welfare as a fourth dimension alongside economic, social, and environmental dimensions. Although no significant differences were observed in overall sustainability between grazing and confined systems, each system exhibited distinct strengths: grazing farms performed better in water and pasture management, whereas confined farms achieved higher scores in productivity, manure management, and selected social indicators. Animal welfare outcomes varied between systems, highlighting the importance of considering this dimension independently within sustainability frameworks. These findings support system-specific strategies and continuous improvement across all sustainability dimensions. Future research should include larger sample sizes, additional indicators, and alternative assessment tools to refine sustainability evaluations and support evidence-based decision making for dairy producers and policymakers.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are not available in public datasets, please contact the authors.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

IS	Sustainability Score
GSI	Global Sustainability Index
Welfare Quality	Welfare Quality® cattle assessment protocol

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