# Circular Economy in the Ecuadorian Dairy Supply Chain: Technology, Sustainability and Business Development

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### Abstract

This article analyzes the adoption of circular economy practices in the supply chain of the dairy sector in Ecuador, with an emphasis on their potential to drive technological innovation and sustainable business development. Based on an exploratory descriptive design with a mixed methods approach, the study characterizes the environmental performance of primary producers, processing companies, and consumers, using official statistical sources such as ESPAC, ENESEM, and ENEMDU for the period 2021-2023. The results reveal a partial application of circular strategies, with greater development at the business stage, contrasted with structural limitations in primary production and limited active participation from consumers. Opportunities are identified for implementing clean technologies, digital traceability, and waste reuse mechanisms. The study concludes that the circular economy is not only viable in Ecuador's dairy sector but also represents a strategic pathway to promote sustainability, competitiveness, and resilience in the industry.

### Keywords

Circular Economy, Dairy Sector, Sustainability, Technological Innovation, Ecuador, Business Development



## 1. Introduction

### 1.1. Dairy Supply Chains: efficiency and challenges

The dairy supply chain comprises several interdependent stages that ensure the flow of products from production to consumption. According to Gómez Verjel et al. [1], this chain can be structured into four main stages: dairy farms, collection centers, processing companies, and marketing entities. Complementing this perspective, Huérfano and Meleán [2] emphasize the importance of integration among producers, receivers, collectors, distributors, and consumers to guarantee the availability of dairy products at the right time and place.

Building on these foundational views, Feliciano et al. [3] describe the common logistical phases within the dairy sector as production, transportation, processing, and distribution. These phases are influenced by key variables such as seasonality, the geographical location of suppliers, and the type of dairy products being handled. Furthermore, Borawski et al. [4] and Heinzova et al. [5] identify critical operational challenges in the sector, notably the short shelf life of dairy products, fluctuations in production volumes, and the high demands for logistical efficiency.

Adding to this, Zheng et al. [6] highlight that the perishable nature of dairy products necessitates highly precise logistical practices to preserve the cold chain throughout all stages. Manufacturers, in this regard, bear the responsibility of maintaining product quality across the supply chain. Factors such as production volume, geographic dispersion of suppliers, and seasonal variability further complicate system efficiency.

Taken together, these complexities underline the urgent need to adopt technological tools and efficient management systems that support traceability and sustainability across the entire dairy supply chain. Within this context, it becomes increasingly relevant to explore how such logistical dynamics can be

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aligned with circular economy strategies, particularly through the implementation of reverse logistics practices in the dairy sector this being the central objective of the present study.

### 1.2. Circular Economy and Innovation in Agroindustry

The Circular Economy (CE) offers an alternative to the linear model, emphasizing resource regeneration, extended product lifecycles, and waste minimization—principles especially relevant in agro-industrial contexts with high organic waste and dependence on natural inputs. Lindahl and Dalhammar define CE as a system maintaining materials in continuous use through regeneration, recycling, or reuse. This systemic view supports the Sustainable Development Goals by reducing emissions and conserving resources.

Within this framework, reverse logistics becomes a critical strategy for recovering value from used products or waste, reducing costs, and strengthening consumer relationships. In the dairy sector, it enhances environmental performance and supports sustainable business models. Ecuador's Circular Economy White Paper prioritizes the dairy industry for its high water use, substantial waste generation, and potential for circular practices [1]. Key opportunities include improving energy and water efficiency, reducing waste, valorizing by products like whey, and fostering public–private partnerships[7]. Clean technologies, ecodesign, business training, and reverse logistics for packaging and material recovery are highlighted as transformative levers.

These factors underscore the strategic role of reverse logistics in CE and the need to assess its adoption in environmentally impactful sectors such as dairy—an objective central to this study. The adoption of sustainable technologies is a core driver in transforming the dairy supply chain toward circular economy models. In Ecuador, studies highlight clean technologies and process automation as essential for reducing water and energy use, improving efficiency, and minimizing waste, thereby enhancing both environmental and operational performance.

Digital traceability has gained relevance as a tool for monitoring each production stage, ensuring quality, facilitating packaging recovery, and improving waste control—thus reinforcing supply chain circularity. Additionally, ecodesign, life cycle assessment, and cleaner production practices are identified as key strategies for shifting from linear to regenerative models. These approaches enable compliance with environmental regulations, respond to evolving market demands, and create sustainability-based competitive advantages.

Assessing the application of these practices in Ecuador's dairy sector is therefore crucial to gauge circular maturity and its alignment with reverse logistics—central to this study.

## 2. Conceptual and Regulatory Framework

Ecuador's legal framework provides the normative foundation for advancing a sustainable development model based on circular economy principles, aligned with constitutional environmental rights, international commitments, and public policies promoting innovation and resource efficiency.

The 2008 Constitution recognizes nature as a subject of rights (Arts. 71–74), embedding prevention, sustainability, and shared responsibility as guiding principles [2]. This constitutional mandate underpins CE as a strategy consistent with Buen Vivir. The Organic Environmental Code (COA) supplies technical and legal tools for integrated waste management, pollution prevention, and cleaner production, with Articles 226, 232, and 233 establishing extended producer responsibility and mandating reuse, recycling, and waste valorization[3]. The Organic Code of Production, Commerce, and Investments (COPCI)

[1] Ministry of the Environment. https://www.produccion.gob.ec/wp-content/uploads/2021/05/Libro-Blanco-final-web_mayo102021.pdf

[2] Constitution of the Republic of Ecuador. https://www.defensa.gob.ec/wp-content/uploads/downloads/2021/02/Constitucion-de-la-Republica-del-Ecuador_act_ene-2021.pdf

[3] Código Orgánico del Ambiente. https://www.ambiente.gob.ec/wp-content/uploads/downloads/2018/01/CODIGO_ORGANICO_AMBIENTE.pdf

advances sustainable business practices through tax incentives and preferential financing for sectors adopting clean technologies, ecoefficiency, and environmental certifications [4].

The Organic Law on Inclusive Circular Economy institutionalizes systemic circularity, public–private coordination, grassroots recycler inclusion, and territorial planning based on regeneration. It requires productive actors to prioritize waste reduction, reuse, repair, recycling, and material recovery. Internationally, Ecuador's ratification of the Escazú Agreement reinforces access to environmental information, citizen participation, and environmental justice [5].

The Ecuador Circular Economy White Paper further identifies the dairy sector as a priority, outlining measures to improve water and energy efficiency, valorize organic waste, integrate clean technologies, and strengthen institutional and business capacities. It offers a policy and cooperation roadmap for applying CE principles to key value chains such as dairy agribusiness.

### 2.1. Key Actors in the Ecuadorian Dairy Supply Chain

The Ecuadorian dairy supply chain comprises three main actors, following the functional structure outlined by Gómez Verjel et al. [1] and Feliciano et al. [3], which underpins the differentiated analysis in this study:

- **Primary producers:** Dairy farms—ranging from small to large—responsible for raw milk production, where levels of technology adoption, management practices, and output directly affect system efficiency and sustainability.
- **Processing companies:** Entities that transform milk into products such as cheese, yogurt, and ice cream, concentrating most of the chain's added value and possessing greater capacity to implement clean technologies and circular economy practices.
- **Consumers:** The final link, whose sustainable behaviors—such as choosing eco-friendly products, returning containers, and engaging in recycling—are essential to closing material loops.

### 2.2. Characterization of the Primary Sector

The Ecuadorian dairy industry plays a key role in food security and rural employment. Between 2019 and 2023, daily milk production ranged from 6.6 to 5.58 million liters, with a significant 7% decline in 2021 attributed to postpandemic effects and changing market conditions (see Table 1). In 2023, the Sierra region contributed 77% of national production, with Pichincha (18%) and Azuay (14%) as the leading producing provinces.

Data show higher productivity in the Sierra (7.7 liters/cow) compared to the Coast (4.3) and Amazon (5.5), due to favorable agroclimatic conditions and the availability of natural and cultivated pastures. Most of the dairy cattle (67%) are located in this region.

Regarding the destination of milk, in 2023, 76.98% was sold in liquid form, 15% was processed on-farm, and only 0.14% was wasted (see Figure 1). However, this small percentage represents 7,936 liters of milk wasted per day, primarily concentrated in the provinces of Manabí (59%) and Pichincha (16.8%), due to issues related to transportation, storage, or inadequate milking practices.

In terms of the milking system, analysis is fundamental to understanding production levels and losses in the dairy sector. Manual milking consists of extracting milk by pressing and massaging the cow's teats with the hands, collecting the milk in a container, usually a bucket. In contrast, mechanical milking uses machines that simulate natural suction through teat cups, creating a vacuum to extract milk more efficiently, which is then stored in tanks. In 2023, out of the daily production of 5.58 million liters from 841,529 cows, 62.63% of the milk was obtained through manual milking, while 37.37% was produced mechanically (see Table 2).

Despite manual milking accounting for the larger share of production, it was responsible for 76% of total milk losses—equivalent to 6,063.98 liters per day—whereas mechanical milking contributed

[4]Código Orgánico de la Producción. https://www.gobiernoelectronico.gob.ec/
[5]Economic Commission for Latin America and the Caribbean. https://repositorio.cepal.org/bitstream/handle/11362/43595/S2200798_es.pdf

**Table 1**
Cattle Inventory, Milking Cows, and Milk Production by Region (2019-2023)

| | Sierra | Coast | Amazon | Other areas | National |
|---|---|---|---|---|---|
| Number of Cattle | | | | | |
| **2019** | 2,225,923 | 1,710,130 | 370,19 | - | 4,306,243 |
| **2020** | 2,129,413 | 1,788,156 | 418,355 | - | 4,335,924 |
| **2021** | 2,110,973 | 1,591.390 | 364,567 | - | 4,066,930 |
| **2022** | 2,046,190 | 1,488,274 | 327,247 | - | 3,861,711 |
| **2023** | 2,039,677 | 1,363,680 | 318,957 | 882 | 3,723,196 |
| Number of Milking Cows | | | | | |
| **2019** | 654,326 | 296,683 | 45,494 | - | 996,503 |
| **2020** | 616,168 | 291,375 | 54,977 | - | 962,52 |
| **2021** | 564,166 | 236,336 | 46,213 | - | 846,715 |
| **2022** | 545,149 | 226,251 | 43,664 | - | 815,064 |
| **2023** | 564,662 | 236,835 | 39,958 | 73 | 841,528 |
| Milk production (liters/day) | | | | | |
| **2019** | 5,165,222 | 1,279,022 | 204,542 | - | 6,648,786 |
| **2020** | 4,751,697 | 1,103,319 | 297,825 | - | 6,152,841 |
| **2021** | 4,535,235 | 933,33 | 230,481 | - | 5,699,046 |
| **2022** | 4,371,040 | 900,319 | 231,428 | - | 5,502,787 |
| **2023** | 4,339,952 | 1,019,113 | 221,566 | 502 | 5,581,133 |

**Note:** The table presents annual data on the total number of cattle, milking cows, and daily milk production (in liters) in Ecuador, broken down by region: Sierra, Coast, Amazon, and Undesignated Areas.

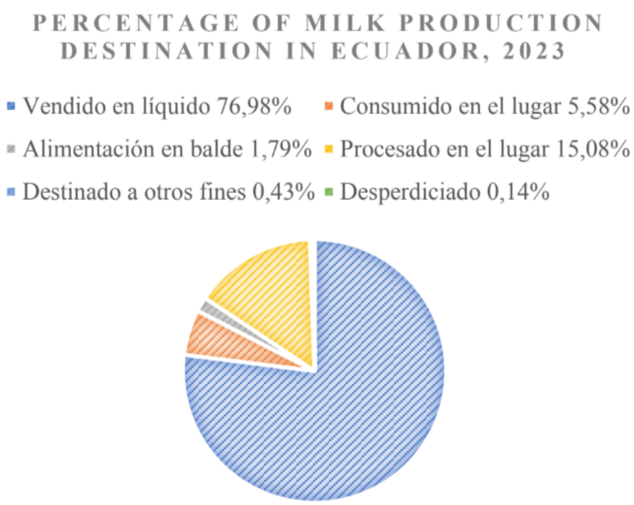


**Figure 1:** Percentage of Milk Production Destination in Ecuador, 2023.

to only 24% of losses (1,872.70 liters daily). This significant disparity highlights a technological gap and structural issue within the sector, especially considering that 80% of the 300,000 dairy producers are small scale farmers with limited access to technology and low profit margins. Closing this gap by promoting the adoption of mechanical milking systems could substantially reduce losses, increase productivity, and improve profitability in the dairy industry.

These conditions directly affect the feasibility of implementing circular economy practices such as whey valorization, energy efficiency, or reverse logistics. Additionally, an informality rate of 38.5% in commercialization further undermines producers' income and reduces sanitary control over dairy products.

From a critical perspective, the primary sector reveals structural vulnerabilities that hinder the

**Table 2**
Milk production and losses by milking system (2023)

| Milking System | Liters Produced | Number of Cows | Liters of Milk Wasted |
|---|---|---|---|
| Mechanical | 2,085,307 | 219,148 | 1,872.70 |
| Manual | 3,495,827 | 622,38 | 6,063.98 |
| Total | 5,581,134 | 841,528 | 7,936.68 |

**Note:** The table shows that manual milking, although it results in a higher production volume and involves more cows, also presents a higher level of waste compared to the mechanical
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transition to circular models. A coordinated intervention is required—one that combines technical assistance, formalization, technological investment, and cooperative schemes to optimize resources, reduce losses, and promote sustainability.

## Business Profile and Circular Performance of the Manufacturing Sector

The dairy product manufacturing sector in Ecuador comprises 204 active companies under ISIC code C1050. Of these, 146 submitted financial statements in 2023. About 46% focus on liquid milk, 23% on ice cream, and 14% on cheese. Guayas (26.6%) and Pichincha (19.9%) host the majority of these companies, reflecting a geographical pattern aligned with national consumption and logistics centers (see Figure 2). Data were obtained from the official company directory, based on 2023 records [6].

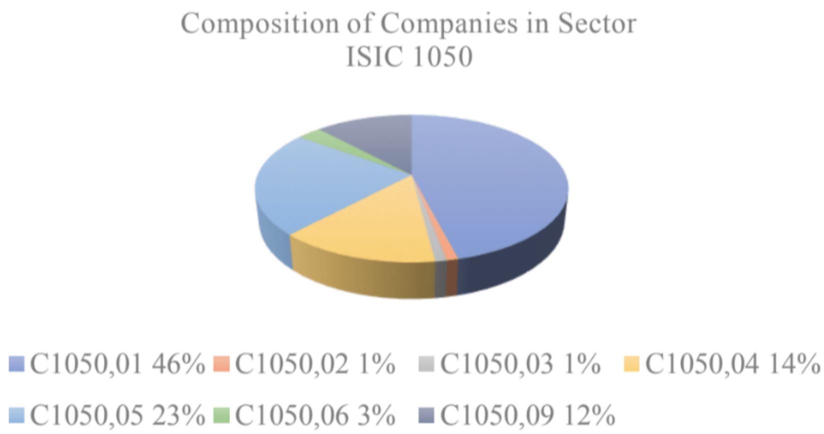


**Figure 2:** Composition of Companies in Sector ISIC 1050.

From an economic perspective, the dairy manufacturing companies included in the ENESEM–MIEAE sample exhibited highly volatile net results: USD 62.1 million in 2021, USD 815 thousand in 2022, and USD 16.3 million in 2023 (see Table 3) [7]. Net profit per unit of product fell sharply, from USD 1.18 in 2020 to just USD 0.00084 in 2022. These figures reflect limited operational efficiency, high sensitivity to production cost fluctuations, and minimal financial flexibility among the surveyed firms.

In terms of environmental performance, 100% of companies reported having staff dedicated to environmental activities in 2020, 2021, and 2022. However, in 2023, a decline was observed, with 15% of companies no longer reporting such personnel (see Table 4). The average number of full-time

[6]Superintendencia de Compañías, Valores y Seguros del Ecuador. https://mercadodevalores.supercias.gob.ec/reportes/directorioCompanias.jsf
[7]Instituto Nacional de Estadística y Censos (INEC). https://www.ecuadorencifras.gob.ec/encuesta-de-informacion-ambiental-economica-en-empresas/

**Table 3**
Financial and operational indicators (2020-2023)

| Indicator | 2023 | 2022 | 2021 | 2020 |
|---|---|---|---|---|
| Net Result (USD) | $16,378,226 | $815,622 | $62,166,405 | $15,551,749 |
| Total Sales (USD) | $987,147,463 | $977,224,198 | $1,294,618,638 | $706,475,271 |
| Total Business Production (USD) | $981,119,599 | $973,904,643 | $1,124,168,326 | $705,769,837 |
| Profit Margin (%) | 1.66% | 0.08% | 4.80% | 2.20% |
| Net Profit per Unit Produced (USD) | 0.016693 | 0.00084 | 0.055 | 1.18 |
| Production Growth (%) | 0.74% | -13.39% | 59.28% | - |
| Sales Growth (%) | 1.02% | -24.51% | +83.25% | - |

**Note:** The table shows the evolution of the company's financial and operational results between 2020 and 2023, highlighting variations in profits, sales, production, and profitability over the period.

environmental workers per company ranged from 2.6 to 3 people, while part-time environmental staff saw a significant decrease, from 7 in 2020 to just 2 in 2023.

Likewise, annual salaries for full-time environmental personnel decreased from USD 794,504 in 2021 to USD 708,110 in 2022, then rose slightly to USD 794,874 in 2023, reflecting adjustments prioritizing operational efficiency without necessarily expanding technical capacity. For part-time staff, salaries dropped sharply from USD 59,832 in 2020 to just USD 11,043 in 2023.

**Table 4**
Trends in environmental staff and salaries (2020-2023)

| Year | Companies with Staff Dedicated to Environmental Management | Number of Full-Time Employees Dedicated to Environmental Activities | Number of Part-Time Employees Dedicated to Environmental Activities | Annual Salaries Paid to Full-Time Employees Engaged in Environmental Activities (USD) | Annual Salaries Paid to Part-Time Employees Engaged in Environmental Activities (USD) |
|---|---|---|---|---|---|
| 2023 | 22 | 71 | 2 | 794 874 | 11 043 |
| 2022 | 26 | 65 | 4 | 708 110 | 5 508 |
| 2021 | 26 | 64 | 7 | 794 504 | 48 272 |
| 2020 | 21 | 53 | 7 | 727 308 | 59 832 |

**Note:** The table shows that between 2020 and 2023 there was a slight increase in the number of personnel dedicated to environmental management, with full-time employees being predominant.

The Ecuadorian manufacturing sector exhibits high variability in its use of water sources, with groundwater extraction standing out as the primary source—particularly in 2022, which recorded an anomalous volume of 568 million $m^3$ (see Table 5). This outlier may be attributable to reporting errors or operational changes. Even excluding this peak, the increasing trend in groundwater use raises concerns about the sustainability of aquifer resources.

Public network water consumption has remained stable (1.2–2.2 million $m^3$ per year), though it suffers from low traceability due to its inclusion in lease agreements or bundled service contracts without itemized records. The use of tanker trucks, notable in 2020 and 2022, reflects infrastructure deficiencies and poses environmental risks due to the intensity of transport activities. Surface water is used by few companies and may be underreported or unregulated.

Overall, there is a clear preference for direct water extraction and weak regulation of water resources. This highlights the need to strengthen traceability, regulate the use of non-conventional sources, and promote efficiency, reuse, and wastewater treatment in order to transition toward a circular water economy.

Wastewater generation in the manufacturing sector has shown a stable trend, with a 40.7% increase in reported volume—from 1.3 to 1.88 million $m^3$—reflecting either enhanced operational capacity or improved reporting practices (see Table 6). Discharges are frequent (14 to 17 hours per day, 26 days per month), indicating continuous industrial activity.

Between 20 and 22 companies reported generating effluents during 2020–2023, although underreporting remains an issue. Between 94% and 100% of wastewater volume is treated, predominantly using

**Table 5**
Summary of water consumption by source and year (2020-2023)

| Year | Public Network | | | Tanker Water | | |
|---|---|---|---|---|---|---|
| | No | $m^3$ | USD | No | $m^3$ | USD |
| 2023 | 20 | 2,168,621 | 2,525,255 | 4 | 4,333,444 | 156,866 |
| 2022 | 21 | 2,234,438 | 2,577,436 | 5 | 4,863,419 | 112,868 |
| 2021 | 23 | 1,224,583 | 2,382,828 | 5 | 2,780,771 | 77,102 |
| 2020 | 17 | 1,714,663 | 2,003,569 | 2 | 4,863,419 | 31,886 |
| **Year** | **Surface Water** | | | **Groundwater** | | |
| | No | $m^3$ | USD | No | $m^3$ | USD |
| 2023 | 3 | 210,696 | 1,139 | 10 | 165,595,008 | 92,320 |
| 2022 | 4 | 1,716,406 | 1,254 | 11 | 568,211,283 | 90,684 |
| 2021 | - | - | - | - | - | - |
| 2020 | 4 | 4,419,936 | 81,708 | 8 | 908,118 | 100,003 |

**Note:** The table presents corporate water consumption between 2020 and 2023, broken down by source (public network, tanker, surface water, and groundwater), showing variations in volume, cost, and type of water intake, with a notable increase in the use of groundwater in 2022.

physical, chemical, and biological technologies—the latter showing significant growth in 2023. However, 2 to 8 companies do not maintain discharge records, and untreated discharges were reported in some years, revealing weaknesses in environmental compliance.

Despite progress in mitigation, no practices of reuse or treated water recirculation were recorded. This indicates that the sector still operates under a control-based approach rather than a water circular economy framework, limiting closed-loop systems and comprehensive resource utilization.

**Table 6**
Wastewater Management of Companies by Year

| | 2023 | 2022 | 2021 | 2020 |
|---|---|---|---|---|
| **Companies that received wastewater** | 0 | 0 | 0 | 0 |
| **Companies that generated wastewater** | 20 | 20 | 22 | 20 |
| **Companies that did not generate wastewater** | 6 | 6 | 4 | 1 |
| **Discharge record (yes)** | 18 | 18 | 17 | 18 |
| **Discharge record (no)** | 8 | 2 | 5 | 3 |
| **Flow generated** $(m^3/h)$ | 304,09 | 290,49 | 284,85 | 205,49 |
| **Discharge hours per day** | 16 | 15,05 | 17 | 14 |
| **Operating days per month** | 26 | 27,16 | 26 | 26,56 |
| **Total wastewater (INEC estimate) ($m^3$/year)** | 1 884 990.96 | 1 827 883 | 1 818 149 | 1 339 438 |
| **Type of treatment** | | | | |
| **Physical treatment** | 21 | 15 | 17 | 16 |
| **Chemical treatment** | 19 | 14 | 18 | 12 |
| **Biological treatment** | 21 | 13 | 13 | 11 |
| **Electrochemical treatment** | 0 | 0 | 0 | 0 |
| **No treatment** | - | 1 | 0 | 2 |
| **Percentage of treated water** | 94% | 96,84% | 95% | 100% |

**Note:** The table presents wastewater management by companies between 2020 and 2023, bhighlighting that none received wastewater, around 20 generated wastes annually, and most maintained records of discharge and treatment, achieving high percentages of treated water.

During the 2020-2023 period, data analysis reveals a clear concentration of corporate efforts on environmental current expenditures, peaking in 2021 (USD 3.04 million) and remaining above USD 1.7 million in other years (see Table 7). Environmental investments, although more limited, reached their highest point in 2022 (USD 908,500), followed by 2021 (USD 547,606) and 2023 (USD 471,612). Meanwhile, the production of goods or services with environmental purposes was virtually nonexistent in 2020 and marginal in subsequent years, with 2021 standing out as the year with the highest reported value (USD 888,400).

**Table 7**
Environmental Production, Investment, and Current Expenditures by Year

| Year | Environmental Production (USD) | Environmental Investment (USD) | Environmental Operating Costs (USD) |
|---|---|---|---|
| 2023 | 96.000 | 124.899 | 1.838.016 |
| 2022 | 1.767 | 908.500 | 1.729.346 |
| 2021 | 888.400 | 547.606 | 3.045.780 |
| 2020 | 0 | 124.899 | 1.594.065 |

**Note:** The table shows that between 2020 and 2023, companies were primarily involved in environmental objectives through current expenditures, especially in environmental protection, while production and investment were minimal and sporadic.

## Consumer Behavior and Environmental Perception

The consumer analysis is based on data from the 2023 ENEMDU survey, which interviewed 8,779 household heads, representing nearly 5 million households [8]. The results reflect a moderate level of environmental awareness, with 38% of households being very concerned about the environment and 42% moderately concerned. However, only 3% actively participated in environmental activities over the past year, revealing a gap between perception and action.

A total of 82% of households still use disposable plastic bags, while only 17% use reusable alternatives. This pattern illustrates a linear consumption culture, with limited adoption of sustainable practices. Regarding perceptions of environmental responsibility, 46% of respondents attribute responsibility to individuals, 41% to companies, and 37% to the government, indicating a shared view, albeit with high institutional expectations. Nevertheless, over 26% believe that caring for the environment increases the cost of living, and 31% see it as an additional burden in terms of time and effort.

These findings point to an urgent need for educational strategies, awareness campaigns, and incentive policies that can mobilize citizen engagement toward concrete actions. The transition to a circular economy cannot rely solely on industrial supply; it requires a cultural shift in consumption and the strengthening of collaborative networks among businesses, citizens, and the State.

## 3. Methodology

This study adopts a mixed-methods research design of an exploratory–descriptive nature, employing a sequential approach that combines quantitative analysis of official surveys and financial records with a qualitative review of regulatory and institutional frameworks.

The characterization of the primary dairy sector draws on data from the Encuesta de Superficie y Producción Agropecuaria Continua (ESPAC) for 2020–2023, conducted annually by the Instituto Nacional de Estadística y Censos (INEC) [9]. ESPAC employs a multiple-frame sampling design, integrating an area-based frame (segments stratified by agricultural land use intensity) with a list frame of key production units, to ensure precision and representativeness at national and provincial levels. In 2023, coverage included approximately 5,768 area segments and 3,499 list frame units, excluding dense urban zones, protected areas, and high altitude lands above 3,000 meters. Data collection was carried out by trained interviewers using structured questionnaires with georeferenced validation. For this study, only dairy producing units were considered, providing variables on total production volume, cultivated area, and livestock counts to characterize the structure and dynamics of the primary sector.

[8] Instituto Nacional de Estadística y Censos (INEC). https://www.ecuadorencifras.gob.ec/hogares/
[9] Instituto Nacional de Estadística y Censos (INEC). https://www.ecuadorencifras.gob.ec/encuesta-de-superficie-y-produccion-agropecuaria-continua-2023/

Microdata on environmental and operational practices were obtained from the Módulo de Información Económica Ambiental en Empresas (MIEAE) of the Encuesta Estructural Empresarial (ENESEM) for 2022 and 2023. ENESEM covers medium and large enterprises nationwide, with disaggregation by firm size and CIIU Rev. 4.0 activity, using a sampling frame based on the Registro Estadístico de Empresas (REEM) 2022. From 16,425 registered enterprises, a probabilistic sample of 4,860 was drawn (mandatory inclusion for large enterprises, random selection for medium enterprises), yielding a 91.3% response rate (4,435 firms). The environmental module provided key variables including use of natural water sources (binary), total environmental investment (USD, log transformed), and number of environmental management employees.

The analytical dataset was structured as an unbalanced short panel comprising 38 observations from 19 manufacturing companies in the dairy sector for 2022 and 2023. A consistency check ensured that the same firms were present in both years and that complete information was available for the selected variables. To estimate the effect of environmental variables on economic and operational performance, two random effects panel econometric models were applied in Stata 19: the first used the natural logarithm of annual revenue as the dependent variable, and the second used the natural logarithm of total production (both in USD). The explanatory variables were: (i) use of natural water sources, (ii) natural logarithm of total environmental investment, and (iii) number of environmental management personnel. The Hausman and Breusch–Pagan tests confirmed the appropriateness of the random effects specification ($p < 0.01$ in both cases). Robustness checks with fixed effects models and Prais–Winsten regression with panel corrected standard errors (PCSE) supported the reliability of the estimates for the 2022–2023 period.

## 4. Integrated Results and Critical Discussion: Progress and Gaps Toward Circularity in the Ecuadorian Dairy Sector

Table 8 presents the results of the random effects model with ln(revenue) as the dependent variable, estimated from an unbalanced short panel (2022–2023). The most influential and statistically significant factor is total environmental investment (ln), with a coefficient of 0.9898 ($p < .001$), indicating that a 1% increase in environmental investment is associated with a nearly proportional rise in revenue. Environmental management personnel show a smaller but positive and significant effect (coef. = 0.0025, p = .022), while water captured from natural sources has a positive coefficient (0.0120) with marginal significance (p = .064).

**Table 8**
Results of the Random Effects Model for In (revenue) Dependent variable: ln(revenue) | Observations: 38 | Groups: 19 | Rho: 0.668

| Variable | Coefficient | Standard Error | Z | p-value | 95% Confidence Interval |
|---|---|---|---|---|---|
| Water captured from natural sources | 0.0120 | 0.0065 | 1.86 | 0.064 | [-0.0007, 0.0247] |
| In (Total environmental investment) | 0.9898 | 0.0040 | 249.59 | 0.000 | [0.9820, 0.9976] |
| Environmental management personnel | 0.0025 | 0.0011 | 2.28 | 0.022 | [0.0003, 0.0046] |
| Constant | -0.9161 | 0.0700 | -13.09 | 0.000 | [-1.0533, -0.7789] |

**Note:** Estimates obtained using a random effects model applied to unbalanced short panel data (2022–2023).

Table 9 reports the model with ln(total production) as the dependent variable. Total environmental investment remains highly significant and positive (coef. = 1.0240, $p < .001$). In contrast, water captured from natural sources now shows a negative and significant effect (coef. = -0.0290, p = .006), and environmental management personnel also display a negative coefficient (-0.0047, p = .018). These shifts in sign suggest that the impacts of resource use and personnel allocation are context-dependent.

**Table 9**
Results of the Random Effects Model for In (total production) Dependent variable: ln(total production) | Observations: 38 | Groups: 19 | Rho: 0.877

| Variable | Coefficient | Standard Error | Z | p-value | 95% Confidence Interval |
|---|---|---|---|---|---|
| Water captured from natural sources | -0.0290 | 0.0105 | -2.75 | 0.006 | [-0.0497, -0.0083] |
| In (Total environmental investment) | 10.240 | 0.0075 | 136.14 | 0.000 | [1.0092, 1.0387] |
| Environmental management personnel | -0.0047 | 0.0020 | -2.37 | 0.018 | [-0.0085, -0.0008] |
| Constant | -15.198 | 0.1330 | -11.42 | 0.000 | [-1.7805, -1.2590] |

**Note:** Estimates obtained using a random effects model applied to unbalanced short panel data (2022–2023).

## Environmental investment as a production driver

The consistently positive and highly significant coefficients in both models confirm that sustainability-oriented investments generate tangible economic and operational returns, supporting prior research linking environmental investment to efficiency gains and competitiveness. This positions environmental investment as a decisive lever for the Ecuadorian dairy sector's transition toward circularity, directly aligning with SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production).

## Ambivalent contribution of environmental management personnel

The positive effect on revenue but negative effect on production suggests that environmental staff may be primarily engaged in administrative, compliance, or reporting functions rather than directly improving operational processes. This functional mismatch can limit productivity gains from human resource allocation in environmental management. Redefining their roles to connect more closely with technical and process improvements could enhance their impact.

## Challenges in water resource management

The negative and significant relationship between natural water intake and production indicates inefficiencies in resource use, potentially due to excessive consumption without adequate treatment or recirculation technologies. Advanced water management systems are essential to reduce dependency on natural sources, lower costs, and support sustainability targets.

## Technological pathways for circularity

Econometric evidence underscores that environmental investment—when directed toward digitalization and automation—can magnify returns. Technologies such as IoT sensors, SCADA systems, blockchain for traceability, and AI-based analytics optimize processes, reduce waste, and improve resource efficiency. Process automation, from milk reception to packaging, strengthens control over energy, water, and emissions, enhancing both environmental performance and competitiveness.

## Waste valorization opportunities

Whey valorization into functional foods, protein supplements, or fertilizers through ultrafiltration and fermentation, along with the conversion of organic residues into biogas or compost, can close material loops. In rural areas, community-based packaging and waste collection models—supported by mobile technologies—can address infrastructure gaps and informality, fostering inclusion in circular systems.

## 5. Conclusions

The Ecuadorian dairy sector shows measurable progress toward circularity, driven mainly by targeted environmental investments that improve operational efficiency and competitiveness. However, production remains concentrated in the Sierra, technological gaps persist, and by-product valorization is still underdeveloped.

Corporate performance is volatile, with environmental management largely reactive and limited adoption of advanced water recirculation, waste valorization, and digitalization systems. While consumer concern for the environment is moderate to high, behavioral engagement remains low.

Key opportunities include expanding whey and organic waste valorization, integrating IoT and automation for resource optimization, and strengthening reverse logistics schemes. Overcoming financing constraints, technological deficits, and weak public–private coordination is essential.

Strategic actions should focus on enhancing Extended Producer Responsibility schemes, promoting green tax incentives, and developing local technical capacities to accelerate the sector's transition toward a resilient circular economy.

## 6. Recommendations and Implications for Future Research

Promote eco-efficient technologies, water reuse, and waste valorization in the dairy sector; strengthen public–private collaboration through targeted regulations, financing, and innovation partnerships; and engage consumers via education and incentives, while future research should assess the long-term economic and environmental impacts of these measures

## Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT and Claude to assist with grammar, style, and spelling checks, as well as with paraphrasing and rewording suggestions. The authors reviewed and edited all content generated with these tools and take full responsibility for the final version of the manuscript.

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