

DOI: https://doi.org/10.48009/4_iis_2026_136

Quantifying food loss in the first mile of the supply chain for perishable broccoli and cauliflower: The case of Colombia

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Abstract

Food losses early in the supply chain threaten sustainability, food security, and rural profitability. This study quantifies the physical and economic impacts of first-mile losses in highly perishable crops and identifies their most vulnerable production stages. Integrating direct quantification, quality-attribute assessments, and the price-based P-method, this approach compares multidimensional losses across different phases. The findings reveal average monthly physical losses of 568 kg of broccoli and 356 kg of cauliflower, totaling approximately 9.5 million Colombian pesos (COP). Quality assessments indicate an additional 927 kg and 537 kg of losses, respectively, while the P-method confirms an economic impact equivalent to 534 kg for broccoli. Losses are non-homogeneously distributed, concentrating primarily in the germination, harvesting, and post-harvest management stages. Ultimately, this study highlights the magnitude of first-mile waste and underscores the need for targeted control strategies in critical phases to optimize production efficiency, mitigate financial impacts, and enhance agricultural sustainability.

Keywords: Agricultural losses, first mile, supply chain, economic quantification, agricultural sustainability

Introduction

According to the Food and Agriculture Organization of the United Nations (FAO), approximately 1.3 billion tons of food are lost or wasted every year, representing nearly one-third of global production intended for human consumption (Flores Rojas, Houmy, & Fawole, 2024), compromising essential natural and economical resources, while exacerbating inequalities in access to food. In Latin America and the Caribbean, the situation is similarly critical, with an estimated 34% of food production, equivalent to 127 million tons annually, remaining unconsumed (FAO, 2019). Furthermore, postharvest inefficiencies have been consistently identified as a central driver of these losses, particularly in horticultural products, where inadequate handling and early-stage logistics significantly affect product quality and availability (Kader, 2003; Argenta et al., 2021). This pattern, observed across both developed and emerging economies, underscores the need for comprehensive and coordinated interventions across agri-food supply chains.

In Colombia, food losses reach 9.76 million tons per year, representing 34% of national production (Alzate-Yepes & Orozco-Soto, 2021). Of this total, 40.5% occurs during the agricultural production stage, equivalent to 3.95 million tons, while 19.8% takes place during post-harvest and storage phases (DNP, 2023). Moreover, fruits and vegetables constitute the most affected category, with losses amounting to 6.08 million tons annually, representing 58% of the national total (DNP, 2016). These figures not only reveal structural deficiencies in infrastructure, technology, and preservation practices, but also highlight critical inefficiencies in early-stage handling processes, particularly in tropical and developing contexts where logistical constraints are more pronounced (Pantastico & Bautista, 1976). Therefore, the evidence points to the urgency of prioritizing targeted interventions in nutritionally significant and highly perishable products.

Several studies have examined food loss from multiple analytical perspectives. Global and systemic approaches highlight the links between food loss, environmental sustainability, and food security (Hu, 2024; Shafiee Jood & Cai, 2016), while structural analyses emphasize the social and ecological challenges embedded in contemporary food systems (De Boni et al., 2022). In addition, research on fresh agricultural produce has focused particularly on post-harvest stages, stressing the role of packaging, cold chain management, and emerging technologies in reducing losses (Onwude et al., 2020; Al-Qurashi et al., 2025). Nutritional and environmental impacts have also been assessed through life cycle approaches (García Herrero et al., 2019), and comparative studies across regions provide insights relevant to the Colombian context (Martindale et al., 2023). Complementary contributions address specific supply chains, such as tomato distribution systems (Zúñiga et al., 2025), climate transition risks (Pérez Pérez et al., 2024), and standardized methodologies for loss estimation (FAO, 2019; Hegnsholt et al., 2020). However, despite these advances, existing research has largely prioritized macro-level assessments, entire value chains, or the storage and refrigeration of products such as grains and tropical fruits. Consequently, there remains a gap in the quantification of food losses occurring in the first mile of the supply chain for highly perishable vegetables such as broccoli and cauliflower, whose post-harvest behavior is particularly sensitive to logistical, socio-economic, and rural infrastructure conditions (Kader, 2003; Rodriguez et al., 2023).

This study addresses this gap through an empirical analysis conducted in Totoró, Colombia. Its contribution lies not only in quantifying first-mile losses, but also in integrating economic, social, and environmental dimensions, positioning food loss as a critical factor for small producer sustainability, regional competitiveness, and food security. By situating the analysis within a rural and underrepresented context, the study responds to recent calls for more localized and value-chain-oriented research in horticultural systems (Rodriguez et al., 2023). In addition, the focus on early-stage postharvest processes aligns with research highlighting the role of handling practices and logistical conditions in determining product quality and loss levels in perishable crops (Kader, 2003; Pantastico & Bautista, 1976). Moreover, evidence suggests that improving coordination and efficiency in initial supply chain stages can significantly enhance performance and reduce waste (Argenta et al., 2021). The research also adopts a territorial approach that recognizes the role of indigenous communities in agricultural production and ancestral land management knowledge. Ultimately, it aims to inform sustainable, culturally relevant solutions aligned with SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production), reinforcing the need for integrated postharvest interventions (Kader, 2003).

The remainder of this study is organized as follows. Section 2 presents the literature review and theoretical framework. Section 3 describes the methodology, data collection and analysis techniques. Section 4 outlines the main results and Section 5 discusses the conclusions, implications, and future lines of research.

Literature review

Food losses

Food losses constitute a structural challenge within global agri-food systems, with significant implications for food security, environmental sustainability, and economic efficiency. Rather than occurring at isolated points, losses are distributed across multiple stages of the supply chain, particularly affecting perishable products such as fruits and vegetables, including highly sensitive crops like broccoli and cauliflower, whose physiological characteristics make them especially prone to rapid postharvest deterioration (Hu, 2024; Shafiee Jood & Cai, 2016). From a systemic perspective, these inefficiencies are not only logistical but also environmental and social, as they contribute to the overexploitation of natural resources and deepen inequalities in access to food (De Boni et al., 2022). In this sense, global assessments emphasize that food loss is intrinsically linked to structural imbalances in food systems, requiring coordinated interventions that go beyond isolated technical solutions (FAO, 2019; Hegnsholt et al., 2020).

Furthermore, postharvest stages have been consistently identified as critical points where losses intensify, particularly in horticultural systems where product quality rapidly deteriorates under suboptimal handling and storage conditions. Foundational work in postharvest physiology demonstrates that inadequate temperature control, mechanical damage, and delays in handling significantly accelerate product degradation, directly translating into commercial losses (Kader, 2003). Empirical studies further confirm that even minor inefficiencies in handling practices can result in measurable economic losses and reduced marketability (Argenta et al., 2021). This is particularly relevant for vegetables such as broccoli and cauliflower, where high respiration rates and sensitivity to handling conditions accelerate quality degradation and increase the likelihood of commercial rejection. In addition, recent contributions highlight that technological gaps and lack of coordination among supply chain actors exacerbate these inefficiencies, limiting the effectiveness of postharvest interventions (Al-Qurashi et al., 2025). Consequently, food losses must be understood as a multidimensional phenomenon integrating physical deterioration, economic impact, and systemic inefficiencies across supply chains (García Herrero et al., 2019).

First-mile food losses

Within this broader framework, the early stages of the supply chain, commonly referred to as the first mile, play a decisive role in determining cumulative loss levels. This stage includes harvesting, initial handling, and transportation from farms to collection centers, where inefficiencies are often more pronounced due to infrastructural and organizational constraints. Empirical evidence indicates that inadequate infrastructure, limited access to technology, and deficient handling practices significantly increase the vulnerability of perishable products during this phase (Villarreal-García et al., 2016; Raut et al., 2019). In tropical and developing contexts, these challenges are further intensified by environmental conditions and logistical limitations. Early research in postharvest handling shows that exposure to high temperatures, mechanical damage, and transport delays accelerate physiological deterioration, particularly in fresh vegetables with high respiration rates, such as broccoli and cauliflower, which are highly sensitive to temperature fluctuations and mechanical damage (Pantastico & Bautista, 1976). Complementary studies demonstrate that operational decisions, such as packaging, loading practices, and transportation conditions, directly influence both physical damage and economic losses (Zúñiga et al., 2025; Martindale et al., 2023). These dynamics are especially critical in the case of broccoli and cauliflower, where inadequate handling during harvesting and transport can lead to rapid visual deterioration, discoloration, and loss of firmness, directly affecting market acceptance.

Food loss measurement and quality indicators

The quantification of losses in perishable products has been addressed through complementary approaches that capture both physical and functional dimensions of deterioration. On one hand, direct measurement

methods estimate losses in terms of kilograms or as a percentage of rejected products across different stages of the logistics chain, including harvesting, collection centers, and transportation (Arcos Hernández et al., 2023). On the other hand, indirect or functional approaches assess losses through the deterioration of quality attributes that reduce the commercial value of the product, reflecting the dynamic nature of postharvest degradation processes (FAO, 2019; Hegnsholt et al., 2020). In this context, physiological and biochemical variables, such as chlorophyll degradation, visual deterioration, mechanical damage, weight loss, respiration rate, and glucosinolate degradation, are widely used as indicators of product quality, particularly in crops such as broccoli and cauliflower, where visual appearance, color retention, and glucosinolate stability are critical determinants of commercial acceptance. These variables are directly linked to market acceptance, influencing attributes such as appearance, firmness, color, freshness, and nutritional content. As a result, postharvest quality functions as a key predictor of commercial losses, since products that fail to meet minimum acceptance thresholds are rejected and recorded as waste (Kader, 2003; Argenta et al., 2021). Consequently, a substantial portion of the literature investigates postharvest interventions and technological treatments aimed at preserving these quality attributes and extending shelf life (Pantastico & Bautista, 1976; Al-Qurashi et al., 2025). These studies collectively underscore that mitigating handling deficiencies and optimizing early logistical decisions are critical to preventing rapid physiological degradation and subsequent commercial discard (Raut et al., 2019; Ghimire et al., 2024).

Beyond these interventions, recent research emphasizes that pre-harvest factors, such as cultivar selection, nutritional management, and climatic conditions, interact with postharvest practices, jointly affecting product quality and shelf life (Romojaro et al., s.f.), which underscores the need for integrated approaches across the supply chain, particularly in the first mile (Rodriguez et al., 2023). In specific crops, such as cauliflower and broccoli, deterioration patterns differ but remain strongly linked to quality-driven rejection processes: browning and tissue degradation are key determinants of marketability in cauliflower, while chlorophyll degradation and floret yellowing are primary causes of rejection in broccoli (Ghimire et al., 2024; Guo et al., 2024). At the same time, alternative strategies such as microwave-assisted dehydration enable the valorization of by-products, contributing to waste reduction within circular economy frameworks (Maldonado & Pacheco-Delahaye, 2003; De Boni et al., 2022). Building on these insights, structured methodologies such as the C-Method, A-Method, and P-Method enable the systematic classification and quantification of physical, qualitative, and economic losses across the supply chain. In particular, the P-Method facilitates the monetization of losses by linking rejected quantities with their corresponding market prices, thereby translating physical losses into economic terms. This relationship is commonly expressed through economic loss estimation models as follows (Parfitt et al., 2010):

$$\text{Economic loss (COP)} = \sum_{i=1}^n (\text{Rejected kg}_i \times \text{Unit price}_i) \quad \text{Ec. 1}$$

This formulation provides a more comprehensive assessment of the financial impact of food losses within supply chains (Hegnsholt et al., 2020; García Herrero et al., 2019). Nevertheless, the absence of a standardized methodological framework continues to generate variability across studies, underscoring the need for integrated and context-specific approaches to loss measurement (Hoehn et al., 2023).

Food losses and Sustainable Development Goals (SDG 2 and SDG 12)

Food losses are closely associated with the achievement of the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production), as their reduction directly contributes to improving food availability, optimizing resource utilization, and minimizing environmental impacts across agri-food systems (FAO, 2019; De Boni et al., 2022). From a systemic perspective, addressing inefficiencies along the supply chain is essential to enhance the overall sustainability and resilience of food systems (Hu, 2024; Shafiee Jood & Cai, 2016). In addition, food loss

reduction carries important socio-economic implications, especially for smallholder farmers whose livelihoods depend on the commercialization of highly perishable crops such as broccoli and cauliflower. Due to their sensitivity to postharvest conditions and first-mile inefficiencies, these products are particularly exposed to quality deterioration, which directly affects income stability and market participation (Llanos, 2020; López, 2021). In this context, strengthening first-mile logistics and improving postharvest management practices emerge as key strategies to enhance rural livelihoods and regional competitiveness (Rodríguez et al., 2023; Argenta et al., 2021). Furthermore, recent studies emphasize the importance of adopting integrated approaches that combine technological innovation, logistical optimization, and institutional support to effectively reduce food losses. Such strategies not only address operational inefficiencies but also align supply chain interventions with broader sustainability objectives, including environmental conservation, economic efficiency, and social inclusion (Al-Qurashi et al., 2025; García Herrero et al., 2019). Consequently, tackling food losses requires a multidimensional perspective that connects technical solutions with long-term development goals.

Finally, the literature reveals key research gaps, including the limited availability of stage-specific loss data for broccoli and cauliflower, the need to more precisely correlate quality indicators with commercial acceptance thresholds, and the insufficient development of loss valorization strategies within circular economy frameworks (Llanos, 2020; López, 2021). Addressing these limitations requires methodological approaches capable of integrating physical, qualitative, and economic dimensions of food loss across different stages of the supply chain. In this context, the present study adopts a structured measurement framework that combines category-based, attribute-based, and price-based methods, enabling a comprehensive and context-specific assessment of first-mile losses in highly perishable horticultural products.

Methodology

This study adopts a structured methodological approach organized into three main phases: (i) process contextualization, (ii) loss quantification, and (iii) results analysis. A mixed-methods approach is employed, integrating quantitative measurement of food losses with qualitative insights derived from field observations and semi-structured interviews. This design enables a comprehensive assessment of food losses in the first mile of the supply chain, particularly at the level of primary agricultural production of highly perishable crops such as broccoli and cauliflower.

Phase I: Contextualization of the production process in the first mile

The first phase consists of an initial diagnosis and detailed characterization of the production process for broccoli and cauliflower, covering activities from germination to postharvest handling. Data were collected through semi-structured interviews with producers and direct field observation, allowing for the identification of key operational stages, critical loss points, and the technical conditions under which production takes place.

Relevant aspects documented include input management, infrastructure conditions, agroclimatic factors, pest and disease incidence, harvesting practices, packaging, and transportation processes. Additionally, the quality classification criteria defined by producers were identified and analyzed, providing the basis for subsequent loss quantification. This phase ensures alignment between empirical observations and the quality-based loss measurement approaches outlined in the literature.

Phase II: Food loss quantification

Based on the initial diagnosis, food losses were quantified in both physical (weight) and economic (monetary value) terms using three complementary methods adapted from Delgado (2017): the C-Method (category-based), A-Method (attribute-based), and P-Method (price-based). These methods allow for the integrated assessment of losses across different dimensions, consistent with the analytical framework presented in the literature.

C-Method (Category-Based Loss Measurement)

This method quantifies losses based on damage observed across product quality categories.

Quantitative weight loss:

$$L_q = Q_{prod} - Q_{PH} + \sum_{i=1}^n C_i \cdot Q_{CiPH} \quad Ec. 2$$

Where:

L_q : total quantitative loss (kg).

Q_{prod} : total production.

Q_{PH} : total quantity after postharvest (kg).

C_i : damage coefficient for category i .

Q_{CiPH} : quantity in category i after postharvest.

n : number of categories.

Economic loss:

$$L_v = V_{prod} - V_{PH} + \sum_{i=1}^n (P_{ideal} - P_i) \cdot Q_{CiPH} \quad Ec. 3$$

Where:

L_v : economic loss.

V_{prod}, V_{PH} : economic value before and after postharvest.

P_{ideal} : ideal price without defects.

P_i : price for category i .

A-Method (Attribute-Based Loss Measurement)

This method evaluates qualitative losses based on sensory and physical attributes such as visual appearance, texture, and odor.

Economic loss by attributes:

$$L_v = \sum_{j=1}^m d_j \cdot Q_{PH} \quad Ec. 4$$

Where:

d_j : economic penalty associated with attribute j .

m : number of evaluated attributes.

Weight loss by attributes:

$$L_q = \sum_{j=1}^m a_j \cdot Q_{PH} \quad Ec. 5$$

Where:

a_j : proportion of product affected by attribute j .

P-Method (Price-Based Loss Measurement)

This method estimates total economic loss by comparing the ideal value of production with the actual value obtained after postharvest.

Direct economic loss:

$$L_v = (Q_{prod} \cdot P_{ideal}) - V_{PH} \quad Ec. 6$$

Direct economic loss:

$$L_q = \frac{L_v}{P_{ideal}} \quad Ec. 7$$

Together, these methods enable a comprehensive quantification of food losses by integrating physical, qualitative, and economic dimensions, consistent with the conceptual framework discussed in the literature.

Phase III: Analysis and interpretation

The final phase involves the analysis and interpretation of results through a comparative assessment between crops (broccoli versus cauliflower), as well as the identification of critical loss points across the production and postharvest stages. Descriptive statistics, including average loss levels and stage-specific distributions, were used to evaluate patterns and variability in food losses.

In addition, results were interpreted in terms of their economic impact on producers, as well as their environmental and social implications. Particular attention was given to the role of first-mile inefficiencies in shaping loss dynamics, allowing for the identification of targeted intervention points. Finally, findings were discussed in relation to broader sustainability objectives, particularly their contribution to Sustainable Development Goals such as SDG 12 (Responsible Consumption and Production).

Results

Phase I. Characterization of the production process in the first mile

Broccoli and cauliflower production in the department of Cauca constitutes an important economic activity, particularly in the municipalities of Totoró, Silvia, and Popayán, where favorable agroclimatic conditions, including altitudes between 1,800 and 2,600 m above sea level, average temperatures of 12–18°C, and fertile volcanic soils, support the cultivation of these highly perishable vegetables (Sarria et al., 2022). According to the Ministerio de Agricultura y Desarrollo Rural (2021), Cauca contributes approximately 12% of Colombia's national production, which is predominantly carried out by small and medium-sized farmers facing significant challenges related to postharvest management, commercialization, and first-mile logistics (Agronet, 2021).

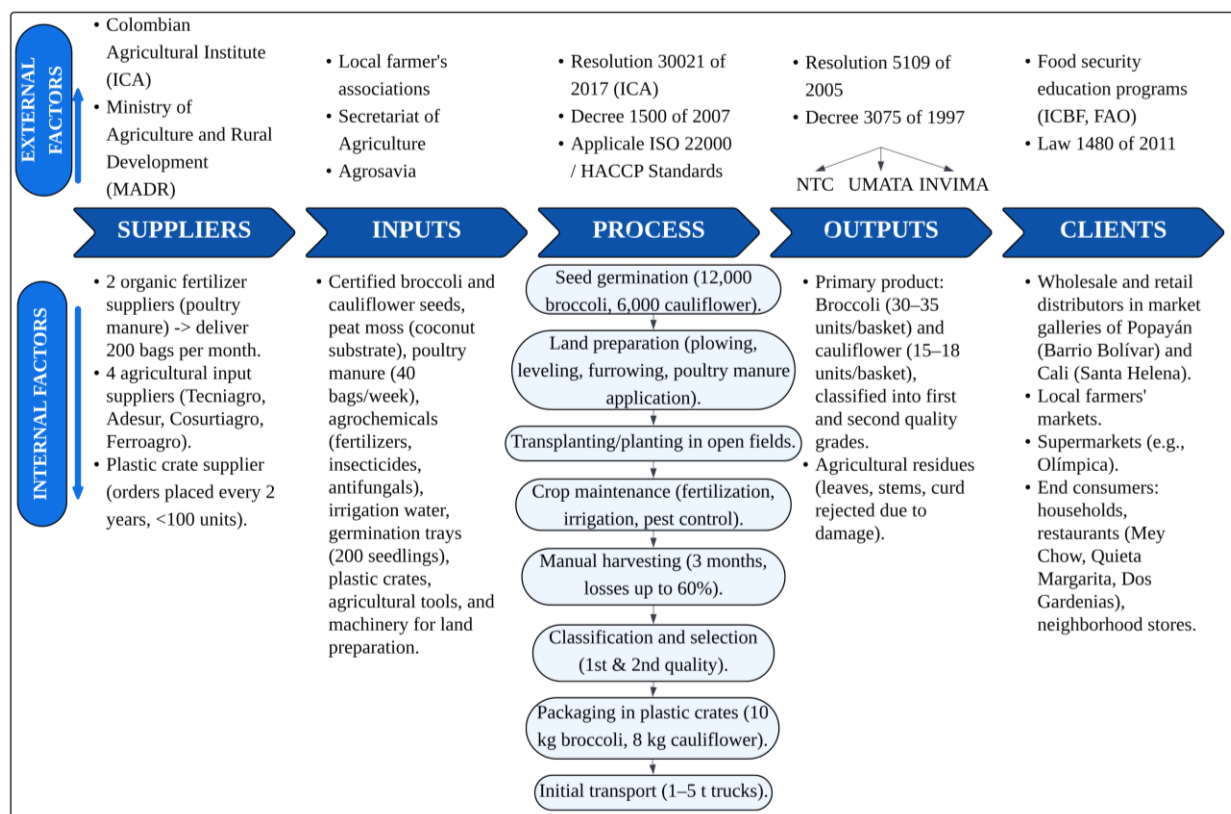
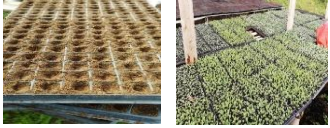


Figure 1. SIPOC of the broccoli and cauliflower production process

Figure 1 summarizes the production process through a SIPOC diagram, while Table 1 describes the main operational stages from seed germination to transportation to collection centers. The process includes land preparation, transplanting, crop management, harvesting, classification, packaging, and transport, together with the principal technical characteristics and potential sources of food loss identified during field observations. This characterization provides the operational basis for the subsequent application of the C-Method, A-Method, and P-Method to quantify physical, qualitative, and economic losses throughout the first mile of the supply chain.

Table 1. Description of the process flow of broccoli and cauliflower in the first mile

Activity	Summary description	Technical data	Risks/losses
	Trays of 200 seedlings in peat moss (coconut substrate). Single cycle.	12,000 broccoli seedlings and 6,000 cauliflower seedlings. Germination time: 30 days.	Fungi, poor irrigation, poor distribution of the substrate.
	Ploughing, levelling and furrowing.	Distance: 40 cm between plants, 45 cm between rows; 50 cm lanes every 4 grooves. Fertilization: 40 bundles of poultry manure /week.	Waterlogging if there are no adequate drains.

Activity	Summary description	Technical data	Risks/losses
Sowing 	Selection of viable seedlings and preventive fumigation.	Transplant depth: 2 cm. Loss: 20 seedlings per tray (10%).	Unfit diseases and seedlings.
Crop Maintenance 	Periodic fertilization and irrigation in drought. Intensive phytosanitary control.	Fertilization every 20 days. Pests: whitefly, aphid, measuring worm, thrips.	Losses due to pests and fungi.
Harvest 	Manual cutting at 3 months after transplanting.	Broccoli: 8–20 cm; Cauliflower: 10–15 cm. Frequency: 3 times/week.	Losses of up to 60% due to temperature and physical damage.
Classification 	Separation into qualities according to size, color and compaction.	First and second quality.	Lower quality product destined for local markets.
Packaging 	Plastic baskets for transport and protection.	Broccoli: 60×40×25 cm, 30–35 units (10 kg). Cauliflower: 60×40×18 cm, 15–18 units (8 kg).	Deterioration due to improper handling.
Initial transport 	Distribution to wholesalers and supermarkets.	Vehicles: 1–5 ton pickups or turbo trucks.	Risk of damage due to transport conditions.

Phase II. Quantification of food loss

Food loss quantification remains one of the principal methodological challenges in agri-food supply chain research due to data limitations, heterogeneous production systems, and the absence of universally accepted measurement frameworks (Hoehn et al., 2023; FAO, n.d.; LAFA, n.d.). To address these challenges, this study applied the C-Method (category-based), A-Method (attribute-based), and P-Method (price-based) proposed by Delgado et al. (2017), which jointly estimate postharvest losses in both physical (weight) and economic (value) terms using primary data collected during fieldwork between October and December 2023. This complementary approach enables a more comprehensive assessment of first-mile losses by integrating commercial quality, product attributes, and market value within a single analytical framework.

The case study was conducted in a specialized horticultural production system located in Totoró, Cauca, where broccoli (*Brassica oleracea* var. *italica*) and cauliflower (*Brassica oleracea* var. *botrytis*) are cultivated under continuous weekly production cycles. Average monthly production reached 9,466 kg of broccoli and 8,300 kg of cauliflower, providing the empirical basis for the application of the three loss quantification methods. According to the commercial quality classification established by the producer, the categorization used in the analysis is presented in Table 2.

Table 2. Categorization of broccoli and cauliflower crops

	Prime broccoli	Second-hand broccoli	Prime cauliflower	Second cauliflower
				
Category	1 (High Quality)	2 (High Quality)	1 (High Quality)	2 (Average quality)
Quantity (kg)	7182	2000	6500	1800
Damage Coefficient (%)	0,02	0,07	0,03	0,08
Price (\$/kg)	4000	3500	3800	3200

C-Method

This methodological approach classifies production into commercial quality categories, assigning specific damage coefficients to quantify losses in both weight (L_q) and economic value (L_v). For broccoli, substituting the parameters into Equation 2 yields a quantitative loss of $L_q = 9466 - 7182 + 2000 + 2.02 + 7182 + 0.07 * 2000 = 284 + 283.6 = 567.6$ kg/month, indicating an estimated monthly first-mile loss of approximately 568 kg. Applying Equation 3 determines the economic loss as $L_v = 9466 * 4000 - 7182 * 4000 + 2000 * 3500 + [(4000 - 4000) * 7182 + (4000 - 3500) * 2000] = \$3,136,000$ COP. For cauliflower, substituting the values into Equation 2 results in a quantitative loss of $L_q = 6835 - 5430 + 600 + 0.02 + 6030 + 0.05 * 600 = 205 + 150.6 = 355.6$ kg/month (approximately 356 kg), while Equation 3 establishes an economic loss of $L_v = 6835 * 4000 - 6030 * 4000 + 600 * 3500 + [(4000 - 4000) * 6030 + (4000 - 3500) * 600] = \$1,420,000$ COP.

A-Method

This method evaluates qualitative losses based on sensory and physical attributes such as color, texture, compaction, and firmness, where each attribute entails an economic penalty calculated through Equations 4 and 5. For broccoli, with a post-harvest volume (Q_{PH}) of 9,182 kg, the economic loss is $L_v = (100 + 200 + 400 + 100) * 9182 + 37864000 - 35728000 = 7345600 + 2136000 = \$9,481,600$ COP, and the attribute-based weight loss is $L_q = (0.01 + 0.02 + 0.03 + 0.01) * 9182 + (9466 - 9182) = 642.74 + 284 = 926.74$ kg/month (approximately 927 kg). For cauliflower, under a Q_{PH} of 6,630 kg, the evaluation indicates an economic loss of $L_v = (100 + 300 + 200) * 6630 + 27340000 - 26220000 = 3978000 + 1120000 = \$5,098,000$ COP and a physical loss of $L_q = (0.01 + 0.03 + 0.02) * 6630 + (6835 - 6630) = 331.5 + 205 = 536.5$ kg/month (approximately 537 kg).

P-Method

The P-Method assesses the overall loss by considering the difference between the expected ideal economic value and the value actually obtained, expressing the gap in both monetary and physical terms through Equations 6 and 7. For broccoli, substituting the parameters yields an economic loss of $L_v = 9466 * 4000 - 35728000 = 37864000 - 35728000 = \$2,136,000$ COP and a physical loss of $L_q = 2136000 / 4000 = 534$ kg/month. Similarly, for cauliflower, the equations indicate a monthly economic loss of $L_v = 6835 * 4000 - 26220000 = 27340000 - 26220000 = \$1,120,000$ COP and a physical loss of $L_q = 1120000 / 4000 = 280$ kg/month.

Phase III. Analysis and interpretation

The comparative analysis between broccoli and cauliflower crops in the first mile, allows identifying loss patterns, dimensioning their economic impact and specifying the critical stages of the process, in order to guide mitigation strategies and optimization of post-harvest management.

Table 3. Comparative Analysis Between Crops

Method	Physical loss (kg/month)	Relative Loss (%)	Economic loss (COP/month)
C-Method (Broccoli)	568	6,00%	\$ 3,136,000
C-Method (Cauliflower)	356	5,20%	\$ 1,420,000
A-Method (Broccoli)	927	9,80%	\$ 9,481,600
A-Method (Cauliflower)	537	7,90%	\$ 5,098,000
P-Method (Broccoli)	534	5,60%	\$ 2,136,000
P-Method (Cauliflower)	280	4,10%	\$ 1,120,000

In the above table, the comparison of the methods shows a significant variability in the estimation of postharvest losses, with a range of affectation in broccoli between 5.6 % and 9.8 %, and in cauliflower between 4.1 % and 7.9 %. This dispersion confirms the sensitivity of the results to the methodological approach applied.

The A-Method, by incorporating qualitative attributes such as color, texture and compaction, tends to magnify the loss estimate by including non-perceptible deterioration in the commercial classification. The C-Method offers an intermediate scenario by integrating both the physical damage and the impact on the market value. In contrast, the more conservative P-Method underestimates losses by restricting itself to the effective economic gap.

From a technical perspective, the results confirm that broccoli is more susceptible to spoilage than cauliflower, given that in all three approaches it shows higher relative losses. This highlights the need to implement more rigorous and differentiated post-harvest management strategies for this crop, especially in the first mile of the supply chain.

Discussion

The findings confirm that the first mile constitutes the most critical stage for food loss generation in highly perishable vegetables, particularly within small-scale agricultural systems characterized by infrastructural and logistical constraints. In the case of Totoró, the estimated losses (21–29%) exceed the global averages reported by the FAO (n.d.), indicating that harvesting, immediate postharvest handling, and transportation remain the principal sources of deterioration in rural horticultural supply chains. Rather than representing isolated operational failures, these losses reflect structural deficiencies associated with limited cold-chain infrastructure, inadequate handling practices, and restricted technological access for smallholder producers. These findings are consistent with previous studies highlighting the influence of logistical inefficiencies on food loss generation in developing agricultural systems (Anand & Barua, 2022; Raut et al., 2019; FAO, n.d.).

Beyond logistical constraints, the results reveal that commercial quality standards themselves constitute an important driver of food loss. Approximately 15% of the total losses were associated with aesthetic classification criteria, where products maintaining adequate nutritional and sanitary conditions were rejected because of size, color, or visual appearance. This finding supports the argument proposed by Hoehn

et al. (2023), who emphasize that a considerable proportion of food losses originates from market requirements rather than food safety concerns. Consequently, reducing food losses requires not only improvements in postharvest technologies but also a reconsideration of commercialization practices and quality standards that currently discourage the marketing of edible products. In this context, the differentiated behavior observed between broccoli and cauliflower further demonstrates that physiological characteristics influence deterioration dynamics. While broccoli exhibited greater susceptibility to chlorophyll degradation, dehydration, and firmness loss, cauliflower was primarily affected by browning and mechanical damage, suggesting that mitigation strategies should be adapted to crop-specific quality indicators rather than generalized across horticultural products.

From an economic perspective, the estimated losses—representing up to one-third of producers' potential income—highlight the substantial opportunity costs associated with postharvest inefficiencies in rural horticultural systems, corroborating previous findings reported by Porat et al. (2018). The combined application of the C-Method, A-Method, and P-Method further demonstrates that food losses should be understood as a multidimensional phenomenon involving physical losses, quality deterioration, and reductions in commercial value. In this regard, the methodological triangulation proposed by Delgado et al. (2017) proved particularly valuable because it captures complementary dimensions of food loss that cannot be adequately represented through a single measurement approach. Likewise, the identification of harvesting, postharvest handling, and transportation as the most critical stages reinforces the need to prioritize investments in cooling technologies, improved handling practices, and refrigerated transportation, in agreement with the recommendations proposed by Onwude et al. (2020) and the evidence reported by Boiteau and Pingali (2022).

Finally, the implications of these findings extend beyond operational efficiency and directly contribute to broader sustainability objectives. Reducing first-mile food losses supports Sustainable Development Goal 2 (Zero Hunger) by increasing the effective availability of nutritious food, while simultaneously advancing Sustainable Development Goal 12, particularly Target 12.3, through the reduction of food losses across production and supply chains. However, achieving these objectives requires more than technological investments alone. Strengthening producers' technical capacities through continuous education and knowledge transfer is equally important for improving postharvest management and first-mile logistics. In this context, Massive Open Online Courses (MOOCs) represent a promising complementary strategy because they facilitate scalable and flexible access to technical training, particularly for geographically dispersed rural communities. As demonstrated by Briceño-Egúsqiza and Rodríguez-Serra (2025), MOOCs enhance knowledge accessibility and support the development of practical competencies through digital learning environments. Integrating these educational initiatives with agricultural extension programs could therefore improve producers' decision-making capabilities, encourage the adoption of best postharvest practices, and ultimately contribute to more resilient, efficient, and sustainable agri-food supply chains.

Conclusions

The broccoli and cauliflower production system in the first mile in Colombia shows strong agronomic potential due to favorable agroecological conditions and experienced farmers. However, this potential is constrained by persistent structural inefficiencies in technification, post-harvest management, and producer organization, which result in significant food losses and reduced economic performance. Estimated losses of 924 kg/month (USD 4.56 million/month), equivalent to 5.7% of total production, reflect systemic inefficiencies rather than marginal operational issues, with direct implications for farmer profitability and sustainability. The convergence of multiple quantification methods further highlights the importance of integrated approaches to accurately capture the scale of these losses.

The evidence indicates that most losses are preventable, shifting the problem from technical limitations to structural and managerial gaps. Addressing these requires coordinated interventions across infrastructure, logistics, and collective organization. Priority actions include the implementation of cold chain systems, temperature-controlled transport, strengthened pest and disease management, farmer training in post-harvest practices, and the promotion of producer associativity through collection centers. The economic rationale is clear: the cost of inaction outweighs investment needs, as efficiency gains and loss reductions would substantially improve both profitability and sustainability.

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