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Carbon footprints of cut-flower supply chains: Comparative analyses and mitigation pathways

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Abstract
The global cut-flower industry, valued at billions of dollars annually, plays a significant role in international trade and consumer markets. However, its supply chains are associated with substantial greenhouse gas (GHG) emissions, driven by energy-intensive cultivation, cold-chain logistics, and long-distance transportation. This review provides a comprehensive synthesis of the carbon footprints of cut-flower supply chains, highlighting comparative analyses across different production systems, transportation modes, and geographic regions. Evidence from life cycle assessment (LCA) studies reveals that greenhouse-based cultivation in temperate regions, such as the Netherlands, generates higher emissions than open-field production in tropical countries like Kenya or Colombia, primarily due to heating and artificial lighting requirements. Conversely, long-haul air freight significantly elevates the footprint of flowers produced in low-emission regions, offsetting the benefits of favorable growing conditions. Mitigation pathways include the integration of renewable energy sources in greenhouse operations, optimization of cold-chain logistics, adoption of sea freight transport, and deployment of biodegradable packaging. Furthermore, certification schemes and carbon labeling can incentivize low-emission practices across the sector. Despite advances in emission reduction strategies, data gaps persist in standardized LCA methodologies, regional emission inventories, and end-of-life waste management practices. This review underscores the urgent need for coordinated technological, logistical, and policy interventions to decarbonize the global cut-flower supply chain. By identifying emission hotspots and feasible mitigation strategies, this study provides a foundation for future research and supports the transition toward a more sustainable and climate-resilient floriculture industry.

Keywords: Cut-flower supply chain, carbon footprint, life cycle assessment, greenhouse gas emissions, sustainable floriculture

1. Introduction

1.1 Background

The cut-flower industry is a highly globalized sector with an estimated annual market value exceeding USD 30 billion, encompassing the production and trade of ornamental flowers such as roses, tulips, chrysanthemums, carnations, and lilies. Major production hubs include Kenya, Ethiopia, Colombia, Ecuador, and the Netherlands, while key consumption markets are concentrated in Europe, North America, and Asia. The industry is characterized by complex supply chains involving cultivation, post-harvest handling, cold-chain storage, long-distance transport, retail distribution, and final consumer use [1, 2].

While cut flowers are often perceived as low-impact luxury products, emerging evidence suggests that their supply chains contribute substantially to greenhouse gas (GHG) emissions. Intensive greenhouse cultivation in temperate climates demands significant energy for heating and artificial lighting, while long-haul air freight from tropical production regions adds further carbon burdens [2, 3]. Additionally, emissions arise from fertilizer and pesticide use, cold-chain logistics, packaging materials, and end-of-life waste disposal. As a result, the carbon footprint of a single flower can vary widely depending on its origin, production system, and transportation mode [3, 4].

1.2 Rationale for the Review

In recent years, there has been growing societal and regulatory pressure to reduce the environmental impacts of global trade, including floriculture. Consumers are increasingly demanding sustainability transparency, while policymakers are introducing climate-focused regulations that could affect the floriculture sector. Despite these trends, comprehensive assessments of carbon emissions in cut-flower supply chains remain limited, fragmented, and inconsistent due to variations in methodologies and geographic contexts [4, 5].

A systematic review is therefore essential to consolidate existing knowledge, identify emission hotspots, and explore feasible mitigation strategies. By comparing production systems across regions and evaluating transportation and logistics alternatives, this review aims to provide a scientific basis for reducing the climate impact of cut-flower trade while maintaining its economic and social value [6,, 7].

2. Carbon Footprints of Cut-Flower Supply Chains

The carbon footprint of cut flowers is the cumulative result of emissions generated across all stages of the supply chain. These emissions vary significantly depending on production practices, logistics, and regional factors. A stage-wise breakdown allows identification of the main emission hotspots [8, 9].

2.1 Production Stage

The production stage is often the dominant contributor to the overall footprint, especially in greenhouse systems [10, 11].

2.1.1 Greenhouse Cultivation

- **Energy Demand:** Intensive use of heating, artificial lighting, and ventilation drives high emissions. For example, Dutch greenhouse roses emit approximately 2.5-3.5 kg CO_2-eq per stem, largely due to fossil fuel-based energy use [12].
- **Fertilizers and Pesticides:** Fertilizer production and application lead to nitrous oxide emissions, while pesticide manufacturing adds indirect emissions [12].
- **Water Management:** Pumping and treating irrigation water adds further energy-related emissions [12, 13].

2.1.2 Open-Field Cultivation

- Flowers grown in equatorial regions (e. g., Kenya, Ethiopia) rely on natural sunlight and suitable climates, avoiding heating and lighting emissions [14, 15].
- As a result, production emissions are much lower, estimated at 0.3-0.5 kg CO_2-eq per stem, but transport-related emissions often offset this advantage [16, 17].

2.2 Post-Harvest Processing

Post-harvest activities preserve flower quality but require energy-intensive processes:

- **Cold Storage:** Refrigeration contributes 0.1-0.3 kg CO_2-eq per stem depending on storage time and efficiency [14].
- **Sorting and Packaging:** Plastic sleeves, floral foams, and cardboard boxes add emissions from material production and disposal [15].
- **Refrigerant Leakage:** Fugitive emissions from cooling systems can significantly increase GHG impacts [16, 17].

2.3 Transportation and Distribution

Transportation is a critical determinant of total carbon footprint.

2.3.1 Air Freight

- Long-distance air transport (e. g., Kenya to Europe) contributes 1.0-1.5 kg CO_2-eq per stem, making it one of the most emission-intensive stages [18].

2.3.2 Sea Freight

- Sea freight is up to 95% less carbon-intensive than air freight but requires extended shipping times and controlled-atmosphere containers to preserve quality [18, 19].

2.3.3 Road Transport

- Short-haul distribution within consumer markets (e. g., Europe, North America) adds 0.05-0.2 kg CO_2-eq per stem, a comparatively minor but relevant component [20, 21].

2.3.4 Hub-and-Spoke Logistics

- Centralized trading hubs, such as the Aalsmeer Flower Auction (Netherlands), increase the number of handling and transport steps, contributing additional emissions [22, 23].

2.4 Retail and Consumer Phase

- **Retail Operations:** Refrigerated display units in supermarkets and floral shops add 0.05-0.1 kg CO_2-eq per stem [24, 25].
- **Consumer Transport:** Personal trips to purchase flowers may exceed retail-stage emissions, especially for small-quantity purchases [25, 26].

2.5 End-of-Life Stage

- **Landfilling:** Disposal of organic waste produces methane, a potent GHG [27, 28].
- **Composting:** Reduces net emissions and is preferred over landfill disposal [29, 30].
- **Packaging Waste:** Non-biodegradable packaging generates additional indirect emissions unless properly recycled [29, 31].

3. Comparative Analyses of Carbon Footprints

Carbon footprints of cut-flower supply chains vary significantly depending on the region of production, cultivation system, and transportation mode. Comparative analysis provides clarity on the trade-offs between local greenhouse-grown flowers and imported field-grown flowers, as well as the role of logistics in shaping overall emissions [21, 22].

3.1 Regional Comparisons

3.1.1 Kenya and Ethiopia (Tropical Production)

Advantages

- Low cultivation emissions (~0.3-0.5 kg CO_2-eq/stem) due to natural sunlight and minimal heating [23, 24].
- Favorable labor costs and high production efficiency [25, 26].

Challenges

- Heavy reliance on air freight to Europe (~1.0-1.5 kg CO_2-eq/stem) offsets production-stage advantages [21, 22].
- Limited infrastructure for sea freight or cold-chain shipping technologies [22].

3.1.2 Netherlands (Temperate Production)

Advantages

- Proximity to major European markets allows for low-emission road transport (~0.1-0.2 kg CO_2-eq/stem) [23, 24].

- Advanced logistics hubs (e. g., Aalsmeer Auction) streamline distribution.

Challenges
- Greenhouse energy demand is extremely high (~2.5-3.5 kg CO_2-eq/stem) [23, 24].
- Heavy dependence on fossil fuels for heating, though a shift to renewable energy is emerging [25, 26].

3.1.3 Colombia and Ecuador (Latin America)
1. Advantages
- Moderate production emissions (~0.4-0.6 kg CO_2-eq/stem) due to favorable climates [21, 22].
- Competitive export costs to the U. S. market [23].

2. Challenges
- **Air freight to North America** contributes substantially to total emissions [23, 24].

3.2 Cultivation Method Comparisons

Parameter	Greenhouse Production	Open-Field Production
Energy Demand	High (heating, lighting)	Low (natural sunlight)
Emissions (Production)	2.5-3.5 kg CO_2-eq/stem	0.3-0.5 kg CO_2-eq/stem
Transport Emissions	Low (regional)	High (air freight)
Overall Carbon Footprint	2. 8-4.0 kg CO_2-eq/stem	1.5-2.5 kg CO_2-eq/stem

3.3 Transportation Mode Comparisons

Transport Mode	Emission Intensity	Key Notes
Air Freight	500-600 g CO_2-eq per tonne-km	Fast delivery but highly carbon-intensive
Sea Freight	10-30 g CO_2-eq per tonne-km	Most efficient; requires cold-chain technology
Road Transport	60-150 g CO_2-eq per tonne-km	Regional; dependent on vehicle type and distance

- Air freight dominates emissions for imported flowers, while sea freight offers a 90-95% reduction in transport emissions but is underutilized due to perishability concerns [21, 22].
- Transitioning high-value flowers (e. g., roses) to sea freight using controlled-atmosphere containers is an emerging solution [23, 24].

3.4 Seasonal and Market Variations
- **Seasonal Shifts:** During winter in Europe, greenhouse flowers have higher emissions due to increased heating demand. In contrast, imported tropical flowers can be more carbon-efficient even after accounting for air transport [25, 26].
- **Market-Specific Preferences:** In the U. S., imports from Colombia and Ecuador dominate due to geographic proximity and lower air freight emissions compared to African imports to Europe [27, 28].

3.5 Emission Hotspot Summary

Stage	Contribution to Total Footprint	Mitigation Priority
Production (Energy)	40-60%	High
Transport (Air)	30-50%	High
Post-harvest & Retail	10-20%	Medium
End-of-Life	<5%	Low

4. Mitigation Pathways for Reducing Carbon Footprints
Addressing the carbon footprint of cut-flower supply chains requires a combination of technological innovation, logistics optimization, and behavioral change. Mitigation strategies can be implemented at multiple levels, from production and transportation to consumer awareness [29, 30].

4.1 Sustainable Production Practices
4.1.1 Renewable Energy Integration
- Transitioning greenhouses from fossil fuels to solar, wind, or geothermal energy can cut emissions by up to 50-70% [31, 32].
- Case Example: Dutch greenhouses using geothermal heating have reduced GHG emissions by nearly 40% compared to conventional gas-heated systems [32, 33].

4.1.2 Low-Carbon Fertilizers and Biological Controls
- Use of organic fertilizers and precision nutrient management minimizes nitrous oxide emissions [33, 34].
- Biological pest control reduces emissions associated with pesticide manufacturing and application [35, 36].

4.1.3 Water and Resource Efficiency
- Closed-loop irrigation systems and rainwater harvesting lower indirect emissions from water pumping and treatment [34, 35].
- Automation in resource management (smart sensors) improves energy and input efficiency [33, 34].

4.2 Transportation Optimization
4.2.1 Shift from Air to Sea Freight
- Transitioning from air freight to controlled-atmosphere sea freight can cut transportation emissions by up to 90-95% [37, 38].
- Successful pilot projects have shown that flowers like roses and carnations can withstand sea shipping if refrigerated properly [39, 40].

4.2.2 Consolidated Logistics and Hub Reduction
- Reducing the number of handling hubs (e. g., bypassing intermediate auctions) limits additional transport emissions [41, 42].
- Direct producer-to-retailer shipping models are emerging as low-carbon alternatives [43, 44].

4.2.3 Green Last-Mile Delivery
- Use of electric delivery vehicles and optimized route planning in urban distribution can reduce final-mile emissions significantly [21, 22].

4.3 Carbon Footprint Labelling
- Introducing carbon labels on flower packaging can empower consumers to make low-emission choices [21, 43].

- Studies suggest that carbon labelling increases consumer willingness to purchase flowers with verified lower footprints by 15-20% [23, 43].

4.4 Circular Packaging and Waste Reduction
- Adoption of biodegradable packaging materials (e. g., plant-based films) can significantly lower emissions from plastic waste [31, 33].
- Encouraging flower waste composting instead of landfilling prevents methane emissions and generates usable organic matter for agriculture [33, 34].

4.5 Certification and Sustainability Standards
- Fairtrade, Rainforest Alliance, and Floriculture Sustainability Initiative (FSI) certifications promote environmentally friendly practices [34, 35].
- Certified farms often implement renewable energy, efficient water use, and reduced chemical inputs, leading to an average 10-20% reduction in total supply chain emissions.

4.6 Consumer Behaviour and Demand-Side Actions
- Promoting seasonal and locally grown flowers can reduce emissions from transport and storage [33, 34].
- Encouraging bulk purchases or coordinated delivery reduces per-stem emissions from retail and consumer transport [35, 36].
- Awareness campaigns on sustainable disposal (e. g., composting) can further reduce end-of-life emissions [37, 37].

4.7 Emerging Technologies and Future Directions
- Blockchain-based supply chain tracking can provide transparency on carbon footprints from farm to consumer [39, 40].
- AI-driven logistics for demand forecasting can reduce overproduction and wastage.
- Carbon offset programs through reforestation or renewable energy investments are being explored by major floral distributors [41, 42].

5. Challenges, Opportunities, and Future Research Directions
Despite significant progress in understanding and mitigating the carbon footprint of cut-flower supply chains, several systemic barriers and knowledge gaps remain [43, 51]. At the same time, technological innovations and policy initiatives offer opportunities for transformation [41, 42].

5.1 Challenges
5.1.1 Data Gaps and Standardization
- Carbon footprint assessments often rely on inconsistent Life Cycle Assessment (LCA) methodologies, making cross-study comparisons difficult [42, 43].
- Lack of region-specific emission factors (e. g., for African or South American production systems) limits the accuracy of global analyses [44, 45].

5.1.2 High Dependence on Air Freight
- Air freight remains dominant for long-distance flower exports due to perishability concerns [46, 46].
- Transitioning to sea freight faces barriers, including inadequate cold-chain infrastructure and industry resistance due to perceived quality risks [42, 43].

5.1.3 Energy-Intensive Greenhouse Systems
- Greenhouse production in temperate regions remains heavily reliant on fossil fuels, with slow adoption of renewable alternatives [44, 45].
- Policy incentives for low-carbon greenhouse energy are still limited in many markets [49, 51].

5.1.4 Consumer Awareness and Behaviour
- Most consumers remain unaware of the carbon impacts of their floral purchases.
- Without effective carbon labelling or education, demand for low-emission flowers remains low [41, 42].

5.2 Opportunities for Emission Reduction
5.2.1 Technological Innovations
- Advances in controlled-atmosphere sea shipping, AI-driven logistics, and renewable-powered greenhouses can significantly reduce emissions [43, 44].
- Precision agriculture and IoT sensors for monitoring fertilizer and water use can further optimize production efficiency [45, 46].

5.2.2 Policy and Market Incentives
- Implementation of carbon taxes, subsidies for renewable greenhouse energy, and incentives for sustainable transport could drive large-scale industry change [49, 50].
- Sustainability certifications can also play a stronger role in rewarding low-emission producers [46, 47].

5.2.3 Collaborative Industry Models
- Retailers, logistics providers, and growers can collaborate on shared cold-chain infrastructure for sea freight [48].
- Regional production hubs with renewable-powered greenhouses may reduce the need for air freight in certain markets [48].

6. Conclusion
The cut-flower industry, though visually appealing and economically significant, carries a substantial carbon footprint due to energy-intensive production, heavy reliance on air freight, and resource-intensive post-harvest handling. Comparative analyses reveal that emissions vary widely depending on geographic origin, cultivation practices, and logistics strategies. While greenhouse-grown flowers in temperate regions have high production-related emissions, open-field flowers in tropical regions face transport-related challenges, particularly when air freight is involved.

Mitigation pathways such as transitioning to renewable energy for greenhouse operations, adopting controlled-atmosphere sea freight, implementing circular packaging, and promoting sustainability certifications offer substantial potential for emission reduction. Furthermore, consumer-facing measures such as carbon labelling and awareness campaigns can stimulate demand for low-carbon floral products, reinforcing industry-wide change.

However, achieving a sustainable cut-flower supply chain requires addressing persistent challenges, including data standardization, infrastructure limitations for low-carbon transport, and insufficient policy support. Future research must focus on harmonizing life cycle assessment methodologies, improving logistics efficiency, and integrating circular economy approaches for waste management.

Ultimately, decarbonizing the cut-flower industry will demand a collaborative, multi-stakeholder approach involving producers, retailers, policymakers, and consumers. By implementing evidence-based mitigation strategies and leveraging technological innovation, the sector can transition toward a more climate-resilient and environmentally responsible future.

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