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Potential impacts of carbon pricing on vegetable cold chains

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ABSTRACT

The urgent need to address climate change has prompted growing interest in carbon pricing mechanisms as tools for reducing emissions in food systems. This review explores how carbon pricing may affect vegetable cold chains, which rely on energy-intensive, temperature-controlled networks essential for preserving produce quality and limiting food loss. While carbon pricing can serve as an incentive for adopting energy-efficient technologies, renewable energy, and sustainable logistics practices, its implementation can also trigger adverse consequences. These include increased operational costs, potential disruptions to supply chains, food affordability challenges, and public health concerns, particularly for vulnerable populations. Drawing on global evidence, this paper discusses both the enabling conditions for carbon pricing (when applied to vegetable cold chains or relevant stages within them) to deliver environmental benefits and the risks of socio-economic trade-offs, including potential impacts on labour, equity, and food security. Mitigation strategies, such as revenue recycling, targeted subsidies, and hybrid policy designs, are also discussed. Overall, the paper emphasizes the need for carefully designed carbon pricing mechanisms tailored to the structure of vegetable cold chains to ensure a just and effective transition to low-carbon food systems.

1. Introduction

Cold storage, which refers to controlled environments that maintain low temperatures is a vital component of cold chains that help to reduce spoilage, extend shelf life, and ensure the safety of perishable foods (Mercier et al., 2017; Dong et al., 2022). For vegetables, which often deteriorate rapidly at ambient temperatures, cold storage enables prolonged marketable shelf life (Gallagher and Mahajan, 2011; Makule et al., 2022). Adequate temperature control is therefore required for the storage and transportation of vegetables to minimise losses and waste, but also to minimise risks of foodborne illnesses (Aung and Chang, 2014a; Mercier et al., 2017). According to certain estimates (Prusky, 2011; Ziv and Fallik, 2021), a substantial percentage of vegetables can spoil before reaching consumers owing to inadequate temperature control. This is a waste of all the resources (water, energy, labour, and land) invested in producing that food (Hall et al., 2009; Chen et al., 2020). Such loss or waste also contributes to environmental degradation, as decomposing food waste generates methane, a potent greenhouse gas (GHG) (Alegbeleye et al., 2022). However, cold chain operations are highly energy-intensive, primarily due to the refrigeration demands of storage and transportation (Han et al., 2021; Marchi and Zanoni, 2022). According to some studies, cold chain logistics are estimated to account for about 4% of the global GHG emissions (Sayin and Peters, 2022; Lin et al., 2025). This energy consumption contributes to environmental degradation, particularly if fossil fuels are used for power (James and James, 2010; Wu et al., 2022). As such, a critical objective of global sustainability efforts is to balance the need for effective cold chain management with the imperative to reduce its environmental impact.

Experts have designed and optimised (or continue to work to optimise) strategies to mitigate emissions associated with maintaining the cold chain for fresh produce (Shabir et al., 2023; Yun and Ülkü, 2023). Pricing carbon, which imposes a price on carbon pollution to account for impacts of GHG emissions that arise from the economic choices of producers and consumers (Baranzini et al., 2017) is one of several efficient strategies to mitigate emissions in many sectors (Tvinnereim and

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Mehling, 2018; Nordhaus, 2019).

Carbon pricing mechanisms such as carbon taxes or emissions trading schemes have the potential to transform how emissions are managed in energy-intensive food sectors (Charlebois et al., 2024). For vegetable cold chains, they could drive investment in cleaner refrigeration technologies, renewable energy use, and more efficient logistics (Sovacool, 2009; Zhou, 2023). However, implementation could also raise operational costs, strain supply chains, and reduce affordability particularly in regions where consumers are already vulnerable (Charlebois et al., 2024). For example, rising cold storage costs could make vegetables less accessible, and contribute to nutrition and health disparities (Fig. 1). Although carbon pricing discussions often focus on high-emission food products such as meat, this review emphasizes the importance of addressing emissions in vegetable cold chains, particularly because of the growing energy footprint due in large part to cold storage and transport, and their essential role in nutrition and food safety (Sayin and Peters, 2022). Overlooking this segment risks unintended consequences for food equity and climate resilience.

This review synthesizes cross-sectoral evidence, from which it infers on the potential impacts of carbon pricing mechanisms when applied to vegetable cold chains. With the overall goal to support policymakers and practitioners working at the intersection of climate mitigation and food system resilience, we explore enabling conditions for success, address potential socio-economic and operational trade-offs, and assess mitigation strategies that could minimize unintended harm.

2. Energy intensity and emission hotspots in vegetable cold chains

Immediately after harvest, vegetables undergo postharvest handling processes such as sorting, washing, grading, and packaging, followed by entry into cold chains to maintain quality and shelf life (Fig. 2). These chains involve energy-intensive stages like refrigerated storage and temperature-controlled transport, each with distinct opportunities for emissions accumulation (Fig. 3).

According to a report by Sayin and Peters (2022) the highest emissions within the food cold chain tend to arise at two primary points: cold storage facilities and the first-leg transport phase. Emissions at the first-leg transport are due apparently to fuel use for transport. In addition to the estimates provided by Sayin and Peters (2022) however, cold storage and transport-related emissions consistently emerge as a predominant hotspot in many relevant supply chain assessments (Tassou et al., 2009; Heard and Miller, 2016). For example, Bin et al. (2022) conducted a life-cycle assessment (LCA) of fruit and vegetable supply chains and found that refrigerated transportation alone accounted for 82% of total emissions. These findings align with those of du Plessis et al. (2023), who analyzed 147 long-haul refrigerated truck trips and reported that refrigeration substantially increased fuel consumption, especially for frozen goods maintained at −25 °C (2.06 L/hr) compared to higher-temperature cargos (1.57 L/hr).

Such variability in emissions is largely driven by differences in refrigeration requirements, which in turn depend on commodity characteristics, haul distance, supply chain design, and ambient environmental conditions (Fig. 3). Longer routes, frozen products, or inefficient trailer configurations can dramatically increase fuel and energy use. Du Plessis et al. (2023) showed that emissions were influenced by ambient temperature, cargo type, load weight, route, refrigeration duration, and the technical specifications of the cooling unit itself. Shen et al. (2023) also demonstrated that energy demands in cold storage facilities vary by product type, with frozen goods requiring disproportionately higher energy inputs due to lower target temperatures. In their study, warehousing operations accounted for nearly half (47.8%) of the facility's total energy consumption, reinforcing the need to target both cold transport and storage in emission-reduction strategies.

3. Review methodology

To meaningfully explore the potential impacts of carbon pricing mechanisms on vegetable cold chains, we conducted a review informed by targeted evidence mapping across intersecting themes: (i) cold chain energy use and emissions, (ii) carbon pricing instruments, and (iii) contextual sustainability trade-offs. We searched four major databases: Scopus, Web of Science, ScienceDirect, and Google Scholar and the search focused on studies published from 2010 to 2025 using combinations of terms presented in Table S1.

Studies were eligible if they provided empirical data, systematic evidence, or modelling results on carbon pricing or emissions mitigation relevant to energy-intensive stages of food systems, particularly cold storage, refrigeration, and cold chain logistics. Although few studies have directly addressed carbon pricing and associated implications for

Fig. 1. Potential socio-economic impacts of carbon pricing along vegetable cold chains.

Fig. 2. Overview of vegetable cold chains.

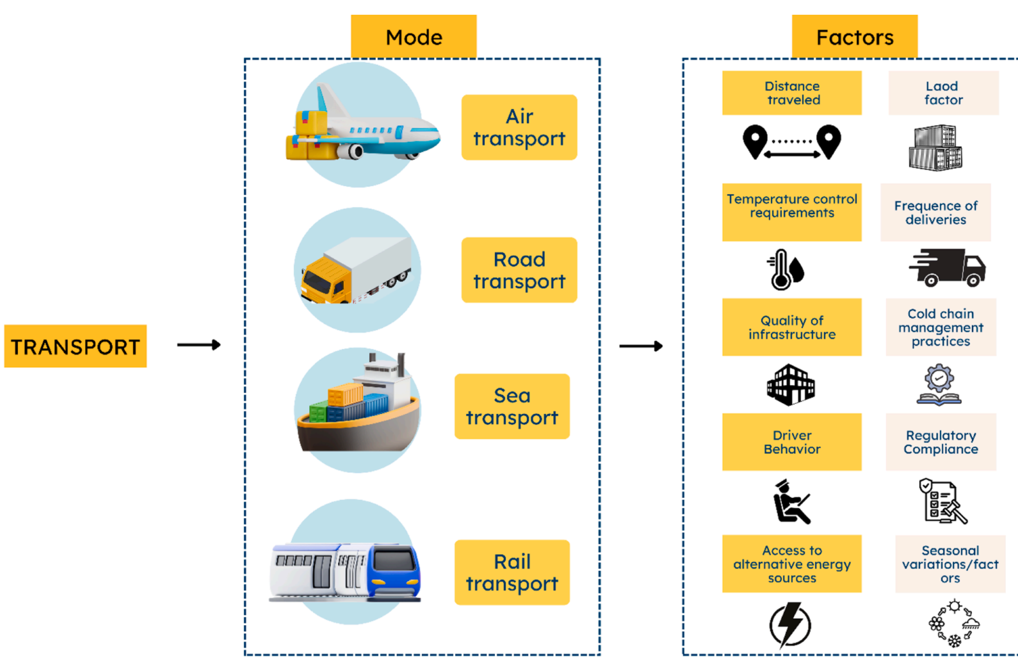

Fig. 3. Modes and factors of transport in vegetable cold supply chains.

vegetable cold chains, we included conceptually and contextually relevant literature/cases from adjacent sectors such as agri-processing, freight for perishable products, refrigerated storage, energy use, emissions profiles, food logistics, refrigeration, and agricultural value chains. Articles that focused exclusively on meat, dairy, or shelf-stable foods with no logistical or environmental parallels to vegetables were excluded. Opinion pieces lacking empirical evidence, and articles without full text or clear methods, were also excluded. Searches were conducted exhaustively within each database until all available results were screened against eligibility criteria. No arbitrary cut-off was applied; instead, the process continued until no new relevant studies emerged.

Considering that direct empirical studies on carbon pricing in vegetable cold chains are somewhat scarce, this study adopts a narrative review approach. This choice allows for the integration of diverse relevant sources, including sectoral case studies, theoretical or conceptual studies, modelling studies / simulation studies, technical or engineering assessments, policy reports and meta-analyses, to synthesize relevant insights.

A recent meta-analysis of 80 ex-post evaluations across 21 carbon pricing schemes found that most carbon pricing policies are still unevaluated, including several major programs, and that empirical data on carbon price elasticity is notably scarce (Döbbeling-Hildebrandt et al., 2024). There is thus a broader evidence gap (not necessarily unique to vegetable cold chains) which warrants research and future evaluation efforts. Of note however, is that vegetable cold chains are increasingly recognized as both climate-sensitive and emissions-intensive segments of the food system, making them highly relevant targets for future carbon pricing interventions (Sayin and Peters, 2022). Anticipating this shift, we adopt a set of transferability criteria to systematically identify and interpret lessons from adjacent sectors. These criteria include but are not limited to similarities in energy demands, perishability, and cold chain dependency (e.g., reliance on diesel-powered cooling or last-mile delivery networks). A summary of the most relevant or principal studies reviewed including sector, intervention, region, and relevance to vegetable cold chains is provided in Table 1.

4. Results and discussions

4.1. Description of carbon pricing mechanisms relevant to vegetable cold chains

Carbon pricing mechanisms including carbon taxes, cap-and-trade systems, and carbon tariffs have been implemented in various sectors to drive emissions reductions and promote sustainable practices (Dolphin and Xiahou, 2022; Döbbeling-Hildebrandt et al., 2024). A recent meta-analysis reported that carbon pricing policies reduce emissions by an average of –10.4% (95% confidence interval: –11.9% to –8.9%), with overall effects ranging from –5% to –21% and adjusting to –4% to –15% after correcting for publication bias (Döbbeling-Hildebrandt et al., 2024). Of note is that the meta-analysis indicates that carbon pricing outcomes depend more on policy design and implementation context than on the price level itself, but carbon pricing can deliver substantial emissions reductions in diverse settings (Döbbeling-Hildebrandt et al., 2024). While these mechanisms have not been specifically designed or directly applied to vegetable cold chains, their application in other sectors such as energy-intensive processes in food supply chains offers valuable insights (Dolphin and Xiahou, 2022). For example, implementation in British Columbia, the European Union and California offer insights into the practicalities of applying carbon pricing within vegetable cold chains, which are energy intensive (Table 2). Drawing on these real-world scenarios, it is possible to anticipate or deduce potential outcomes, operational challenges, and opportunities for vegetable cold chains under similar policies. In our review, we identified five carbon pricing mechanisms that could potentially be applied to vegetable cold chains—carbon taxes, cap-and-trade systems, carbon credits, carbon tariffs, and carbon offsetting—all of which are summarized in Table 2 and discussed below.

4.1.1. Carbon taxes

Carbon taxes directly impose a fee on GHG emissions, effectively raising the cost of carbon-intensive activities such as refrigeration, storage, and transportation in businesses such as vegetable cold chains (Wang et al., 2017; Charlebois et al., 2024).

Evidence from real-world implementation demonstrates how assigning a financial penalty to emissions creates a clear incentive for actors across the supply chain to adopt lower-emission technologies and practices (Benedetti et al., 2025). For example, after British Columbia implemented its carbon tax in 2008, per capita GHG emissions from taxed fuels declined by about 13% between 2008 and 2013, while total emissions covered by the tax fell by 6%. Meanwhile, the province's economy continued to grow at a rate comparable to or slightly better than the rest of Canada, indicating no significant negative effect on overall economic activity (Charlebois et al., 2024; Elgie and McClay, 2013) (see Table 2).

While carbon taxes seem efficient at decarbonizing, they may also create trade-offs particularly for smallholders or retailers operating in low-margin environments. For example, some studies suggest that carbon taxation on refrigerated transport could increase logistics costs for fresh food, especially in fuel-dependent cold chains (He and Sun, 2025).

Strategic revenue use can mitigate these risks. Funds generated from carbon taxes may be reinvested in cold chain upgrades, for instance, through deploying solar chillers in rural markets or subsidizing energy-efficient refrigeration (Bushnell, 2017; Habib et al., 2024). These reinvestments can create a feedback loop that enhances sustainability and support access to safe foods. Effectiveness would however depend on how equitably and consistently carbon taxes are applied. If neighbouring regions or trading partners do not impose similar levies, carbon leakage (a situation where emissions-intensive activities are relocated to areas with less stringent regulations) may occur, and businesses may shift operations to jurisdictions with laxer standards (Jakob, 2021; Köppl and Schratzenstaller, 2023). To the extent feasible, policymakers must therefore coordinate regionally and internationally to ensure that carbon taxes are designed to balance environmental ambition with socio-economic sensitivity. As discussed in a later section (4.4), some evidence indicate that a comprehensive approach rather than the application of any single tool, may more effectively drive emissions reductions along cold chains (Carl and Fedor, 2016; Carattini et al., 2018).

4.1.2. Cap-and-trade systems (Emissions Trading System)

Under a cap-and-trade system, a regulatory authority sets a limit on the total GHG emissions allowed from specific sectors, potentially including the vegetable cold chain (Carl and Fedor, 2016; Verschuuren, 2022). Companies receive or purchase emissions allowances, i.e., rights to emit a certain amount of GHGs and can trade these allowances on the market (Charlebois et al., 2024; Pang and Duan, 2016). Firms that emit less than their cap can sell surplus allowances, while those exceeding their limit must buy additional ones. This market-driven mechanism/dynamic creates a financial incentive for emissions reductions and offers a level of flexibility, as it allows firms to either invest in cleaner technologies or purchase allowances (Du et al., 2016).

According to the meta-analysis by Döbbeling-Hildebrandt et al. (2024), ETS schemes have consistently produced statistically significant emissions reductions, with impacts ranging from –5% to –21%, even after correcting for publication bias (–4% to –15%). This indicates that ETS are effective tools for emission reduction, though the magnitude of efficiency varies substantially across regions and policy designs.

Case evidence illustrates this variation. In China, ETS pilots were associated with average reductions of –13.1% despite low carbon prices (<US$8), largely because they signalled strong government commitment to mitigation (Döbbeling-Hildebrandt et al., 2024). In contrast, the EU ETS delivered more modest reductions of about –7.3%, though its

Table 1
Summary of some principal studies reviewed including sector, intervention, region, and relevance to vegetable cold chains.

Study	Sector/stage	Intervention/mechanism	Region	Relevance to vegetable cold chains
(Tassou et al., 2011)	Retail refrigeration and food cold chain	Refrigeration Optimization	UK	Highlights refrigeration as the largest energy load in fresh produce retail, with retrofit options like VFDs and closed cabinets offering up to 50% energy savings. Quantifies supermarket refrigeration energy use (up to 60% of electricity); helps benchmark emissions hotspots in vegetable retail cold chains
(Heard and Miller, 2016)	Food distribution (retail formats)	Transportation strategies and their environmental impacts	UK	Study highlights the cold chain's role in preserving perishable goods. It also discusses energy consumption, supply chain alterations, behavioural changes impacting food waste, links to GHG emissions, and identifies the need for more research on the environmental impacts of vegetable distribution
(Bushnell, 2017)	Carbon-emitting industries	Policy analysis of revenue uncertainty from carbon pricing	California, USA	Focuses on the California cap-and-trade system, its revenue uncertainty, and the broader implications of carbon pricing as a source of public funds
(Wang et al., 2018)	Fresh food supply chain	Carbon cap-and-trade + refrigerated logistics services	China	Refrigerated logistics and internal carbon trading, including discussions on pricing strategies for refrigerated services
(Dong and Miller, 2021)	Cold storage and early transport	Modelling and quantification of post-farm gate emissions	China	Demonstrates that over 50% of cold chain emissions occur at the first storage and transport stages, underscoring early-chain refrigeration as a major emissions hotspot in vegetable logistics
(Meneghetti et al., 2021)	Long-haul cold chain transport	Photovoltaics refrigeration systems	Europe (Italy)	Offers a tested model for decarbonizing refrigerated transport using solar Photovoltaics.
(Bin et al., 2022)	Fruit and vegetable logistics	Life cycle assessment of refrigerated transport	China	Found that refrigerated transport accounted for 82% of total emissions — key insight for cold chain hotspot identification
(du Plessis et al., 2023)	Refrigerated trucking	Real-world emissions tracking of cold transport	South Africa	Quantified fuel use by temperature range and haul conditions
(Shabir et al., 2023)	Food processing & cold chains	Review of carbon footprint reduction strategies	Global	Identifies emissions reduction potential across cold chain stages (e.g., refrigeration, transport, storage)
(Shen et al., 2023)	Strawberry cold chain	Life-cycle emissions analysis and logistics optimization	China	Provides comprehensive LCA of cold chain emissions, highlights early-chain transport and storage as key GHG contributors and evaluates optimization strategies such as improved routing and cleaner energy
(Yang and Yao, 2023)	Fresh produce supply chain	Cap-and-trade modelling	China	Simulated how cap-and-trade affects emissions, technology adoption, and coordination mechanisms in fresh cold chains
(Karacan et al., 2023)	Operational and technical aspects of cold storage facilities	Analysed energy consumption in cold storages, operating conditions, and the potential for energy savings through proper management and technological improvements.	16 countries (hot & temperate)	Empirical measurements from 67 facilities show up to 30–50 % variation in energy use depending on operational practices; identifies compressor staging, insulation, and defrost strategies as high-impact retrofit targets
(Sayin and Peters, 2022)	Full supply chain	Need for improved data collection and standardized methodologies to quantify GHG emissions in food cold chains.	Global	Emphasizes the need for standardized methodologies to quantify GHG emissions and energy consumption in food cold chains
(Charlebois et al., 2024)	Agri-food sector	Scoping review on carbon pricing	Canada	Reviews the effects of carbon pricing on food affordability and the agri-food sector in Canada
(Habib et al., 2024)	Food system	Conceptual analysis of carbon pricing implications	Global	Discusses risks and design issues in carbon pricing for fresh food systems
(Döbbeling-Hildebrandt et al., 2024)	Economy-wide (multi-sector)	Meta-analysis of ex-post evaluations of carbon taxes and ETS	Global	Synthesizes evidence on carbon pricing effectiveness, highlights the paucity of sector-specific evaluations, and supports need for targeted impact studies
(He and Sun, 2025)	Fresh food e-commerce logistics	Logistics sharing under carbon tax policy	China	Proposes a novel logistics-sharing model that allows E-retailers (often used for vegetable sales) to access superior cold chain infrastructure from T-retailers; addresses carbon pricing implications directly
(Neusel and Hirzel, 2022)	Food cold chain logistics	Stakeholder interviews on energy efficiency drivers/barriers	EU (Germany, Italy and Spain)	Identifies systemic and firm-level factors that influence the adoption of energy-efficient technologies in cold chains. Such insights can meaningfully inform the design of carbon pricing instruments targeting refrigerated vegetable logistics
(Lin et al., 2025)	Cold chain transport (urban and regional)	IoT-based bottom-up carbon emissions model for refrigerated trucks (driving, idling, refrigeration, leakage)	Taiwan	Quantifies emissions across cold transport phases using IoT data and finds driving (62.8–66.9%) and idling (up to 13.9%) are major contributors. Offers insights for logistics on emission hotspots and mitigation via shore power and low-GWP refrigerants.

(continued on next page)

Table 1 (*continued*)

Study	Sector/stage	Intervention/mechanism	Region	Relevance to vegetable cold chains
(Benedetti et al., 2025)	Food trade / border regulation	Carbon Border Adjustment Mechanism (CBAM) applied to UK-EU food trade	UK and EU	Simulates carbon tariffs on food categories including vegetables; estimates potential 25% reduction in imported GHG via trade reallocation; provides product-level emissions insights using MRIO.
(Wang and Du, 2025)	Logistics (transport and storage of temperature-sensitive products)	Application of IoT with LSTM–PSO model for real-time monitoring, dynamic equipment scheduling, and energy optimization	China	Cold chain logistics consumes over 30% of total logistics energy, with refrigerated trucks and cold storage systems accounting for more than 60%. The proposed IoT-based system reduced energy use by ~20%, improved temperature/humidity accuracy to 94%, and shortened transport time by 8.33%. These innovations are directly transferable to vegetable cold chains, where real-time monitoring and energy optimization can reduce spoilage, lower costs, and cut emissions.

LCA = Life Cycle Assessment, MRIO = Multi-Regional Input-Output analysis, ETS = Emissions Trading System, GHG = greenhouse gas, GWP = Global Warming Potential, IoT = Internet of Things, LSTM–PSO = Long Short-Term Memory (LSTM)- Particle Swarm Optimization.

Table 2
Overview of carbon pricing mechanisms and their relevance or potential applicability to vegetable cold chains.

Mechanism	Description	Potential impacts	Example/case study	Potential relevance to vegetable cold chains	References
Carbon Tax	Direct levy on carbon emissions	Incentivizes energy efficiency; may raise operational costs. Meta-analyses confirm taxes are consistently associated with statistically significant emissions reduction	British Columbia's 2008 tax cut per capita GHG emissions by ~13% and total emissions by ~6%, with no negative economic effect.	Transport emissions in vegetable distribution; affordability	(Elgie and McClay, 2013; Murray and Rivers, 2015;
Cap-and-Trade (ETS)	Emissions cap with tradable allowances; creates incentives for low-carbon technology adoption and flexibility in compliance.	Encourages efficiency retrofits, low-GWP refrigerant adoption, and innovation; can improve fresh-keeping and profitability in fresh supply chains through strategic contracts. Risks include higher costs and reduced profits for firms unable to cut emissions internally	Chinese pilots achieved –13.1% reductions despite low carbon prices (<US$8). EU ETS delivered ~–7.3% reductions, with effectiveness improving as allocation rules tightened and schemes matured. Swiss ETS led to weak/ negligible effects. RGGI achieved –21% reduction (partly due to shale gas boom). California Cap-and-Trade funds the F-gas Reduction Incentive Program (FRIP), which incentivizes refrigeration upgrades with low-GWP refrigerants and energy-efficient systems.	Applies to large distributors and cold-storage facilities; allowance costs can incentivize adoption of energy-efficient refrigeration, low-GWP refrigerants, and contractual coordination along fresh chains. Long-term price signals influence investment: effectiveness may increase as schemes tighten over successive phases	(Wang et al., 2018; Yang and Yao, 2023; Döbbeling-Hildebrandt et al. (2024)
Carbon Credits	Certificates for verified emission reductions	Revenue potential; potentially complex for SMEs	Husk Power Systems in India generates revenue from electricity sales and carbon credits related to its biomass and solar mini-grid projects	Innovative use of carbon finance can contribute to scaling sustainable cold chain infrastructure.	(Sevea, 2013)
Carbon Tariffs	Carbon-based import duties	Shifts incentives in global trade	EU CBAM simulation by Benedetti et al. (2025) shows 25% GHG cut in imported foods including vegetables via trade reallocation	Vegetable trade competitiveness (potentially)	(Benedetti et al. 2025)

GWP = Global Warming Potential, ~ = around, SMEs = Small and Medium-sized Enterprises, CBAM= Carbon Border Adjustment Mechanism, EU ETS = European Union Emissions Trading System, RGGI= Regional Greenhouse Gas Initiative.

effectiveness improved over successive phases as regulatory rules tightened illustrating how policy design and scheme maturity can influence outcomes (Döbbeling-Hildebrandt et al., 2024). The Swiss ETS by comparison led to weaker and sometimes negligible emissions reduction effects. However, as the meta-analysis notes, such findings partly reflect methodological limitations and a high risk of bias across several case studies, which makes it difficult to draw robust conclusions for Switzerland —or indeed for any single country—alone (Döbbeling-Hildebrandt et al., 2024). The Regional Greenhouse Gas Initiative (RGGI) in the US, which achieved reductions of –21%, was one of the more effective carbon pricing schemes, though part of this performance was due to external influences such as the shale gas boom (Döbbeling-Hildebrandt et al., 2024).

These findings highlight that effectiveness depends less on nominal carbon price levels and more on design and context — including scheme coverage, allowance allocation, complementary policies, and local energy market structures. For vegetable cold chains, this indicates that ETS could potentially influence investment and operational choices even at low price levels, provided schemes send credible long-term signals to firms and other relevant stakeholders.

Another important dynamic is time. According to the meta-analyses by Döbbeling-Hildebrandt et al. (2024), ETS effectiveness tends to increase as schemes mature and tighten over successive phases. This suggests that cold-chain actors may experience more significant impacts from ETS in the medium to long term, as allowance caps become stricter and low-carbon investments pay off.

The findings of some recent studies also suggest specifically that cap-and-trade schemes can promote sustainability and profitability in fresh produce supply systems. For example, a study by Yang and Yao (2023), indicates that carbon cap-and-trade schemes encourage suppliers to enhance their fresh-keeping efforts to meet consumer demands, and successfully address carbon emissions. The implementation of specific contracts, such as cost-sharing and two-part pricing, was shown to align incentives, leading to improved fresh-keeping activities and increased profitability. The study reported specifically that higher consumer preferences for freshness, coupled with these strategic contract designs, can yield favourable outcomes for both sustainability and profitability within the fresh agricultural supply chain (Yang and Yao, 2023).

California's climate policies, which are partially funded by its cap-and-trade program, provide real-world evidence that such mechanisms can work in practice. The F-gas Reduction Incentive Program (FRIP) directly incentivizes commercial and industrial refrigeration facilities, including those in cold storage, food processing, and food retail, to reduce GHG emissions by investing in energy-efficient technologies and ultra-low GWP refrigerants, contributing to sector-wide emissions reductions as part of the state's broader climate goals.

The application of cap-and-trade systems can however, also be detrimental to businesses that for whatever reasons, struggle to meet emission reduction targets (Stavins, 2008; Carl and Fedor, 2016). For example, a separate modelling study by Wang et al. (2018) showed that under a cap-and-trade system, firms unable to reduce emissions internally may grapple with higher costs and reduced profits due to the need to purchase additional carbon allowances. Yang and Yao (2023) also highlighted that the costs associated with carbon emissions can challenge effective preservation strategies and emphasised the need for coordinated efforts between suppliers and retailers. Factors such as the allocation of allowances, the cap level, the design of the scheme and the monitoring and enforcement mechanisms adopted to ensure compliance, can influence the capacity for implemented cap and trade programs to achieve desired emissions reductions along vegetable cold chains, without exerting significant adverse socio-economic effects (Carl and Fedor, 2016; Babagolzadeh et al., 2020).

4.1.3. *Carbon offsetting*

Carbon offsetting allows companies to compensate for their emissions by investing in projects that reduce or remove an equivalent amount of CO_2 from the atmosphere, such as reforestation or renewable energy projects (Lovell and Liverman, 2010). Businesses in the vegetable cold chain can invest in carbon offset projects to balance out their emissions, which may be a more flexible approach to comply with carbon regulations. For example, they can invest in tree planting projects to absorb CO_2 from the atmosphere (Kollmuss et al., 2008). They could also fund solar, wind, or other renewable energy projects that offset the emissions generated by cold chain operations (Kollmuss et al., 2008). Another potential approach includes supporting local community projects that contribute to emission reductions, such as improved cookstoves or clean water initiatives (Lovell and Liverman, 2010).

One model for integrating carbon offsetting into vegetable cold chains (especially in Low- and Middle-Income Country contexts where decentralized solutions are likely to be more feasible) is Ecozen. Ecozen has implemented off grid solar-powered cold storage units for smallholder vegetable farmers, and evidence indicates that this innovation has reduced postharvest losses and reliance on diesel-powered refrigeration (Tinsley and Agapitova, 2018). Ecozen's model incorporates carbon offsetting by tracking avoided diesel emissions and linking cold-chain operators to voluntary carbon credit markets through certified offset. Farmers or cooperatives using these units can benefit from both operational savings and potential income from selling carbon credits. This example demonstrates potential for quantifiable carbon savings through avoided fossil fuel use, practical integration of renewable energy into cold chains, as well as potential for scaling via carbon markets or public-private investment.

In spite of this (and other) strong evidence indicating that carbon offsetting programs can contribute significantly to global efforts to combat climate change, research indicates that application of offsets should be complemented by direct emissions reductions strategies to ensure meaningful emissions reduction (Lovell and Liverman, 2010).

4.1.4. *Carbon credits*

Carbon credits are certificates that represent the right to emit one ton of CO_2. They can be earned through activities that reduce emissions, such as renewable energy projects or energy efficiency improvements (Mathews, 2008). Companies can earn carbon credits by implementing sustainable practices, such as using renewable energy for refrigeration or optimizing transportation routes to reduce fuel consumption (Mneimneh et al., 2023). A practical example is the Refrigerant Carbon Credit Pilot, where food retailers receive Refrigerant Carbon Credits (RCCs) for replacing high-Global Warming Potential refrigerants with more sustainable alternatives. These credits are sold at premium prices, providing both environmental and financial returns for cold-chain investments (Climate Impact Partners 2022). Another notable example is Husk Power Systems in India, which generates revenue from electricity sales and carbon credits related to its biomass and solar mini-grid projects (Table 2).

The process of earning carbon credits requires accurate measurement and reporting of emissions reductions (Haya et al., 2020). Efficiency of the process is thus contingent on accurate data collection and transparency within the cold chain (Mathews, 2008). Many carbon credit programs involve verification processes such as third-party verification of emissions reductions to ensure that claimed reductions are real and quantifiable (Mathews, 2008). Effective implementation can therefore be beneficial in several other ways. For example, it can promote accountability in emissions reporting, as well as enhance credibility and trust among stakeholders (Haya et al., 2020). It can also improve stakeholders' understanding of their emissions profiles and aid the identification of areas for improvement (Haya et al., 2020). Selling carbon credits can also provide an additional revenue stream for businesses and other relevant stakeholders (Oh and Chua, 2010; Chhetri et al., 2024).

Carbon credit markets can however, be subject to volatility, which may affect the financial viability of projects aimed at generating credits (Lohmann, 2010). Perhaps more importantly, fluctuations in credit prices can impact the willingness of stakeholders to invest in emissions reduction initiatives (Lou et al., 2023). Another potential drawback is that navigating the carbon credit system can be complex, particularly for smaller stakeholders in the vegetable cold chain (de Castro Moura Duarte et al., 2024; Schofield et al., 2024). The administrative burden of participating in carbon credit programs may consequently deter some from engaging, limiting the overall effectiveness of the system (Schofield et al., 2024). The distribution of benefits from carbon credits may also be inequitable. Larger, more resourceful stakeholders may be better positioned to take advantage of carbon credit opportunities, potentially leaving smaller producers at a disadvantage (Schofield et al., 2024).

4.1.5. *Carbon tariffs*

Carbon tariffs can be applied to vegetable cold chains by imposing fees on the carbon emissions associated with the production, transportation, and storage of vegetables (Ma et al., 2021). For countries that export vegetables, carbon tariffs can be applied to imported goods to level the playing field. This means that imported vegetables would be subject to tariffs based on their carbon emissions, to encourage foreign producers to adopt greener practices. Under such schemes, it would be mandatory that importers pay the same carbon price as domestic producers, with the aim to remove the cost advantage that carbon-intensive imports could otherwise enjoy (Cosbey et al., 2019; Benedetti et al., 2025). A notable example is the EU's Carbon Border Adjustment Mechanism (CBAM), which entered its transitional reporting phase on October 1, 2023, and will begin financial implementation in 2026 (Benedetti et al., 2025). While currently covering imports like steel, cement, and fertilizers, CBAM taxes carbon-intensive inputs (e.g., nitrogen fertilizers used in vegetable production) and could, therefore, serve as a precedent or at least some components of it may inform carbon pricing in vegetable cold chains, even though cold chain logistics are not directly included (Benedetti et al., 2025).

To implement this scheme, the first step is to assess the carbon footprint of the entire vegetable cold chain, including production, transportation, storage, and distribution (Shabir et al., 2023). This assessment identifies the major sources of emissions, such as refrigeration systems, transportation methods, and energy sources used in the cold chain (Shabir et al., 2023). Based on the carbon footprint assessment, governments or regulatory bodies can establish carbon tariffs that impose a fee on the carbon emissions associated with the 'offending' cold chain operations. This tariff can be structured to reflect the emissions intensity of different practices, to ultimately encourage companies to adopt more sustainable methods.

Like other carbon pricing mechanisms, the revenue generated from carbon tariffs can also be reinvested into promoting low-carbon technologies or other sustainable alternatives within the cold chain (Bushnell, 2017; Cosbey et al., 2019). For instance, the revenue generated from carbon tariffs can be reinvested as subsidies or funding for energy-efficient refrigeration systems, electric vehicles for transportation, or renewable energy sources to power cold storage facilities (Cosbey et al., 2019) (Table 1).

4.2. Potential socio-economic impacts of carbon pricing on vegetable cold chains

Refrigeration operates within a broader system influenced by the global environment and climate dynamics. For instance, emissions from refrigeration interact in feedback loops with ambient temperatures and contribute to broader climate change processes (Jradi and Riffat, 2014). When carbon pricing is applied to vegetable cold chains to promote sustainability therefore, it can generate far-reaching socio-economic effects (Fig. 1). These outcomes depend on factors such as policy design, the carbon intensity of existing refrigeration systems, business practices, market conditions, regulatory frameworks, and the specific characteristics of individual supply chains (Sovacool et al., 2021; Döbbeling-Hildebrandt et al., 2024). These differentiated effects are summarized in Table 3, which presents some challenges and potential benefits for different cold-chain stakeholders.

Based on available evidence, it is reasonable to postulate that for cold-storage operators and transporters, the most immediate impact could be higher energy and fuel costs, particularly for operations dependent on leak-prone refrigerants (Dong and Miller, 2021; Sayin, and Peters, 2022). These same actors can, however, also benefit from adopting low-GWP refrigerants, energy-efficient systems, and optimized logistics. Such measures reduce costs over time and may also create branding opportunities, for example those related to 'green' cold chains (Han et al., 2021; Xie et al., 2023). This incentivization of the adoption of cleaner refrigeration technologies is positive, but retrofitting processes may temporarily disrupt critical operations such as temperature control and delivery timelines (Table 3). This could, depending on the specific circumstances, increase the risk of produce spoilage (Åkerman et al., 2021; Sovacool et al., 2021). Small-scale producers who lack resources to adopt clean technologies may also be excluded, exacerbating socioeconomic and infrastructural inequities (Sovacool et al., 2022).

For smallholder farmers and low-income consumers, price pass-through from higher logistics costs may reduce affordability of vegetable commodities, exacerbate nutrition gaps (Santos, 2022; Nsabiyeze et al., 2024), and worsen public health outcomes (e.g., reduced intake of nutrient-rich vegetables can increase risk of certain non-communicable diseases) (Känzig, 2021;Vermeir et al., 2020).

Equipment suppliers and service providers may grapple with transitional costs from retrofits and downtime, but they also stand to gain from rising demand for innovative insulation solutions, modular cold rooms, and performance-linked leasing models (Table 3) (Sayin and Peters, 2022). Similarly, financial institutions and aggregators may deal with challenges related to uncertain returns on investment, although climate-linked financing instruments and bulk procurement arrangements could unlock new opportunities (Stram, 2016; Frew et al., 2021). These variable effects underscore the need for context-sensitive carbon

Table 3
Summary of potential stakeholder-specific impacts, challenges, and opportunities from carbon pricing in vegetable cold chains.

Category of impact	Stakeholders likely to be significantly affected	Potential challenges/implications	Opportunity for innovation & sustainability	References
Environmental impact	Cold-storage operators, transporters, end consumers	• Higher electricity/fuel bills (CO_2 e-based levies) • Leak-prone refrigerants may be more expensive	• Adoption of "green-cold" branding to signal low-emissions logistics and attract premium buyers • Investment in low-GWP refrigerants and energy-efficient refrigeration systems can reduce long-term costs and emissions	(Niu et al., 2024)
Social factors	Smallholder farmers, low-income consumers	• Price-pass-through can raise retail prices, risking reduced vegetable intake • risks for nutrition gaps or inequities to widen	• Differentiation via "carbon-neutral" labels to capture niche buyers • Cold-storage cooperatives can pool resources to fund energy-efficiency upgrades and distribute the resulting cost savings back to stakeholders	(Schoneveld, 2022)
Technical factors	Equipment suppliers, maintenance service providers	• Retrofit costs for efficient insulation or low-GWP refrigerants can be significant, especially for small cold chain operators. • Downtime losses when upgrades lag	• Innovative insulation solutions and prefabricated modular cold-chain infrastructure designed considering the needs of smallholder operators. • Pay-for-performance leasing arrangements that link equipment rental fees directly to achieved energy savings.	(Gong et al., 2023)
Economic factors	Financial institutions, SMEs, aggregators	• Difficulty accessing finance for cold-chain upgrades due to uncertain ROI • Carbon pricing may amplify capital constraints, especially for small operators • Aggregators may grapple with high upfront costs without coordinated financing	• Green financing instruments (e.g., climate-linked loans, outcome-based grants) • Aggregator-led bulk procurement models for energy-efficient equipment • Carbon-credit-linked leasing and insurance products for low-emission cold chains	(Neusel and Hirzel, 2022)

GWP = Global Warming Potential, ROI = Return on Investment, SMEs = small and medium-sized enterprises

Table 4
Operational design elements and research priorities for carbon pricing implementation in vegetable cold chains.

Design element	Key considerations	Pilot & research opportunities (propositions)
Emission-source mapping	• Stage-specific GHG data collection across pre-cooling, transport, storage, and retail • Disaggregation by commodity, region, actor type (e.g. smallholders vs. exporters)	• Build LCA models using methods such as those by Bin et al., (2022) • Compare hotspots for various vegetable commodities (as relevant) e.g. tomato vs. leafy greens in two (or more) comparable regions
Pricing-mechanism design	• Alignment with vital realities	• Pilot a fuel levy on refrigerated trucks • Test a tradable-allowance scheme for major cold-chain hubs
Cost distribution & revenue recycling	• Protect low-margin actors (e.g. SMEs) • Earmark revenues for clean-tech subsidies, relevant consumer offsets, and nutrition programs	• Grant funding for solar cold rooms (e.g. Ecozen model) • Voucher program for natural-refrigerant retrofits among smallholders
Monitoring, Reporting & Verification	• Enable digital MRV tools (automated tracking of temperature, energy use, and transport metrics), standard protocols, and third-party audits	• Field trial of IoT-enabled temperature & emissions sensors or trackers • Cost-benefit study of third-party audits in urban vs. rural nodes
Food security & equity safeguards	• Tiered pricing, basic-vegetable exemptions, tradable credits for ultra-low-carbon suppliers • Inclusive governance with informal actors and consumer groups	• Design an adaptive tariff for staple vegetables • Engage smallholder cooperatives in governance pilots
Policy coherence & integration	• Harmonize with energy, trade, health, food-safety regulations and SDG goals (2, 7, 13) • Reduce compliance overlaps	• Map synergies between carbon pricing and national energy subsidy reforms • Co-pilot a carbon-pricing + food-safety audit integration
Transition pathways & timing	• Phased implementation (e.g., over 5–10 years) • Scenario modelling of gradual vs. immediate price impacts on emissions and affordability	• Model emissions & cost impacts under three rollout speeds • Quasi-experiment or other approaches comparing two regions with different phase-in schedules
Research priorities	• Paucity of direct empirical evidence on vegetable cold chains • Need for scenario modelling, elasticity and distributional analyses, and firm-behaviour studies	• Studies on the price elasticity of consumer demand for refrigerated vegetables—i.e., how changes in price (such as resulting from carbon pricing) affect consumer purchasing behaviour. • Cluster-randomized trial of hybrid tax + rebate scheme on smallholder networks

GHG = Greenhouse gas, LCA = Life Cycle Assessment, MRV = Measurement, Reporting, and Verification, SMEs= Small and Medium-sized Enterprises, vs. = versus, IoT- Internet of Things. SDG= Sustainable Development Goal

pricing policies that minimize inequities and enable innovation and sustainability across the vegetable cold chain (Table 4).

4.3. Strategies to cushion the adverse effects of carbon pricing mechanisms for vegetable cold chains

Revenue from carbon pricing can be recycled to strengthen vegetable cold chains; for example, by cushioning vulnerable actors and accelerating the transition to low-carbon technologies. There is some evidence suggesting that earmarking revenues for targeted subsidies or direct grants can offset the costs of energy-efficiency retrofits in cold storage facilities and subsidize adoption of greener refrigeration systems (Sumner et al., 2011). Complementary training programmes, covering best practices in efficient operation, maintenance of relevant equipment, and alternative cooling methods can also build technical capacity and resilience throughout the value chain, and should be prioritised. Designing flexible pricing schemes that incorporate differentiated rates or temporary exemptions for food-security-critical sectors can provide an incentive for emission reductions but could also contribute to assuring that essential vegetable cold-chain services remain affordable. It would be vital to consider and pursue close collaboration with finance ministries, industry associations, and regional stakeholders during policy development, as this could help tailor compensation mechanisms to local needs and administrative realities. Finally, aligning national frameworks with international standards and directing a portion of carbon revenues toward public-health initiatives or consumer-side subsidies can safeguard vegetable accessibility for low-income households and reinforce the equitable distribution of benefits from carbon-pricing reforms (Ambasta and Buonocore, 2018; Bataille et al., 2018; Lencucha et al., 2020; Chepeliev et al., 2021).

4.4. Integrated and multifaceted approaches to carbon pricing for vegetable cold chains

While the focus of this paper is carbon pricing, available evidence indicates that pricing tools are often most effective when integrated with complementary strategies and technologies (Carattini et al., 2018; Alkaabneh et al., 2021; Charlebois et al., 2024). In any case many carbon pricing tools that have been implemented to date, have been applied as part of a broader policy strategy rather than as standalone measures (Döbbeling-Hildebrandt et al., 2024). It is therefore essential to examine relevant integration opportunities to understand how carbon pricing can interact with other measures to amplify (or otherwise influence) emissions reductions, socio-economic trade-offs, and unlock innovation in vegetable cold chains.

Complementary approaches are separate, non-pricing policies that reinforce the effects of carbon pricing, such as subsidies or regulations. Hybrid approaches, which combine elements of multiple emissions reduction strategies, are particularly relevant to cold chains because they can address emissions from multiple sources such as refrigerants, energy use, fuel consumption, and spoilage simultaneously (Bushnell, 2017; Fu et al., 2023). This flexibility allows stakeholders to better tailor solutions to their specific operational contexts (Liu et al., 2019). Several studies provide concrete examples of relevant synergistic pairings. Alkaabneh et al. (2021) highlight how carbon taxes can be more effective when integrated with land sparing and innovations in storage technologies. Similarly, researchers argue that integrating carbon taxes with incentives for energy-efficient practices can amplify overall emissions reduction (Bushnell, 2017; Liu et al., 2019).

In practice, integrated approaches have already been adopted with tangible results. California's comprehensive cap-and-trade program combines a pricing mechanism with targeted subsidies and rebates for low-GWP refrigerants and energy-efficient refrigeration technologies. This policy mix has accelerated investments among cold storage operators and logistics firms, supporting both rapid decarbonization and operational sustainability (Bang et al., 2017) (Table S2). In India, the Ecozen initiative, which displaces diesel-powered refrigeration and links users to voluntary carbon markets where avoided emissions can be monetized through certified credits illustrates how renewable energy deployment can be combined with active participation in voluntary carbon markets. (Tinsley and Agapitova, 2018; Copeland LP, 2025).

Complementary certification schemes are another approach that significantly contribute to or facilitate emission reductions. The Green Freight Asia program, a voluntary sustainability standard, encourages freight and logistics operators in Asia to adopt fuel-efficient practices and cleaner transport technologies. These schemes are contextually implemented or applied alongside national carbon pricing policies or energy subsidies and have been shown to reinforce incentives for route optimization and fleet modernization (Green Freight Asia, 2022) (Table S2). Similarly, the European Union's Energy Efficiency Directive synergizes with the EU ETS by mandating energy audits and efficiency improvements in refrigeration facilities. This regulatory combination compels actors within cold chains to identify and implement practical energy-saving measures, complementing the carbon cost signals generated by pricing mechanisms (Table S2).

Innovative business models deploying renewable energy and thermal storage have also gained ground in regions with limited grid access. For example, solar-powered modular cold rooms with integrated thermal storage, such as those implemented by ColdHubs in Nigeria, offer affordable and scalable solutions for reducing emissions and improving fresh produce preservation. These initiatives often leverage local government subsidies and international climate finance, demonstrating how technology, finance, and policy can coalesce to address the multifaceted challenges of decarbonizing vegetable cold chains in diverse contexts (Amjad et al., 2023).

These examples indicate that integrated approaches—where carbon pricing provides the foundation and is complemented by targeted technological innovations, financial incentives, voluntary standards, and other policy instruments—can achieve greater emission reductions than any single intervention on its own.

Despite their advantages however —including flexibility and greater potential for scalability—integrated approaches may also present some challenges. Coordinating multiple strategies and technologies often requires significant upfront investment in training, infrastructure, and management capacity (Fu et al., 2023). The associated costs can be prohibitive, particularly for small-scale actors with limited financial resources, and may create or contribute to equity gaps in implementation. Accurately measuring and verifying emissions reductions from integrated approaches may also be challenging. Establishing robust metrics, harmonized reporting frameworks, and reliable monitoring systems is essential but can be technically complex and resource intensive. Furthermore, aligning diverse stakeholders—governments, private firms, producers, and consumers—around common goals and standards may be difficult, potentially leading to fragmented implementation and reduced effectiveness (Liu et al., 2019).

4.5. *Designing carbon pricing mechanisms for vegetable cold chains: Practical considerations and future research directions*

While carbon pricing holds promise for decarbonizing vegetable cold chains, its success depends on a cohesive, well calibrated policy architecture that accounts for the sector's heterogeneity and socio-economic context (Sovacool et al., 2021). To be sure, 'success' here refers to the capacity of carbon pricing to drive meaningful emissions reductions in vegetable cold chains without compromising affordability, resilience, or social equity. To translate ambition into actionable change, we propose an integrated framework that combines rigorous emissions mapping, context-sensitive pricing instruments, equitable cost-sharing mechanisms, transparent monitoring systems, and targeted research and pilot initiatives (Table 4).

A critical first step is to establish a robust baseline through disaggregated GHG accounting across all stages of the cold chain i.e. precooling, refrigerated transport, storage, and retail (these stages can be seen in Fig. 2). Stakeholders could consider some methodologies such as those by Bin et al. (2022); Costa Jr et al. (2023); Flammini et al. (2024); and Barth et al. (2025) or suitably modified versions thereof, for the identification of emissions hotspots by commodity, region, and actor type (smallholders versus exporters, for example) (Table 4). Such detailed emissions mapping has great potential to pinpoint where interventions will yield the greatest reductions, as well as inform the calibration of price signals to reflect the true carbon intensity of each segment of vegetable cold chains.

Once baseline emissions are quantified, policymakers should then choose one or more suitable carbon-pricing instruments (detailed in Section 4.1 and summarized in Table 2) that reflect the operational realities of vegetable cold chains. For example, emissions cap can spur investment in advanced refrigeration technologies. Whichever mechanism is adopted, it must drive meaningful emissions reductions without imposing disproportionate cost burdens on low-margin operators.

Equitable cost distribution is equally essential. To ensure that vulnerable actors aren't priced out or otherwise marginalised, revenues generated through pricing must be channelled back into cleaner technologies, (for example, through subsidies for solar-powered cold rooms or grants for natural-refrigerant retrofits) and used to cushion affordability impacts on low-income consumers. For instance, pilot programs such as Ecozen's off-grid solar chillers (funded by carbon-credit revenues tied to avoided diesel emissions) have simultaneously reduced postharvest losses and created new income streams for smallholder cooperatives (Copeland LP, 2025).

Transparent Monitoring, Reporting, and Verification (MRV) systems are central to credibility and allow for adaptive management. Drawing on relevant models such as the EU ETS model, digital tracking tools, standardized protocols, and independent third-party audits should be tailored to refrigerated logistics and storage facilities. Field trials in diverse contexts (especially in low- and middle-income settings) that can reveal cost-effectiveness thresholds and guide the evolution of MRV requirements are desirable and should be prioritized. Currently, there are no reliable estimates to quantify the level of emissions reductions along vegetable cold chains attributable to carbon pricing programs alone. However, generating such data is essential and should be integrated into a robust MRV system. This would enable the development of science-based targets for emissions reduction and support evidence-driven policy refinement.

Safeguards to protect food security and equity are non-negotiable. Adaptive pricing tiers, basic commodity exemptions, or tradable allowances for ultra-low-emission suppliers can prevent smallholders and low-income households from being priced out of the market. Inclusive stakeholder engagement, i.e. considering informal actors and consumer groups in design, formulation and implementation can help ensure that carbon pricing complements, rather than conflicts with, existing food-safety, trade, and energy regulations.

Finally, strategic research and pilot opportunities must fill critical evidence gaps (Döbbeling-Hildebrandt et al., 2024). Scenario modelling should compare pure tax regimes with hybrid mechanisms, while elasticity studies can quantify how wholesale price changes transmit to consumer demand. Trade-off analyses between affordability and emission reductions, interaction assessments with energy-subsidy reforms, and empirical explorations of firm behaviour under different carbon prices will provide the empirical backbone needed for scalable, equitable policy design.

5. Conclusions

This review highlights the critical but often underexplored contribution of vegetable cold chains to food system emissions. While carbon pricing has more commonly been evaluated in the context of high-emission sectors like meat or industry, our synthesis shows that the energy-intensive stages of vegetable cold chains (particularly refrigeration, early transport, and storage) are significant contributors to post-farm emissions. These findings highlight the need for more targeted policy tools that address emissions emanating from vegetable cold chains, without compromising affordability, nutrition, or food safety.

This literature review draws from a diverse and growing evidence base, but it is important to highlight the scarcity of sector-specific data on actual carbon emissions and price responsiveness in vegetable cold chains. Many studies rely on modelled or proxy data, and few empirically evaluate how carbon pricing directly affects cold chain actors or consumer behaviour.

To support effective policy design, our findings suggest the need to integrate carbon pricing with complementary tools such as targeted subsidies, green financing, or nutrition-focused rebates to cushion impacts on smallholders and low-income consumers. Pilot initiatives, for example, outcome-based grants for cold-chain retrofits or digital Measurement, Reporting, and Verification (MRV) systems can build an evidence base for scaling context-appropriate interventions.

Future research should prioritize empirical studies that assess the real-world impacts of carbon pricing on vegetable cold chain operations, affordability, and access. This includes but is not limited to analyses of price elasticity to understand how changes in vegetable prices, driven by emissions regulation, might influence consumer demand and dietary outcomes. Scenario modelling (that compares phased versus immediate implementation approaches and evaluates distributional effects) for different supply chain actors can also offer insights into the most equitable and effective pathways. The goal should be to build the empirical and analytical foundation needed to design carbon pricing policies that reduce emissions, but safeguard the essential role of vegetables in healthy, affordable diets.

Ethical statement

We hereby affirm that:

1- The material submitted is our own original work, which has not been previously published elsewhere.
2- The paper is not currently being considered for publication elsewhere.
3- The paper reflects our own research in a truthful and complete manner.
4- All sources used are properly disclosed (correctly cited).
5- We have read and understood ethical research requirements.
6- No animals or human specimens were used.

CRediT authorship contribution statement

Oluwadara Alegbeleye: Conceptualization, Formal analysis, Methodology, Investigation, Writing – original draft, Writing – review & editing, Resources, Validation, Visualization. **Girma T. Kassie:** Methodology, Writing – review & editing, Validation, Visualization. **Adama Ndour:** Methodology, Writing – original draft, Writing – review & editing, Software, Visualization, Validation. **Muluken Elias Adamseged:** Methodology, Visualization, Validation. **Aruni Athukorala:** Methodology, Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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