LETTER

# Turning Voyage Time into Value: An Integrated Shipping-and-Aging Intervention for Irish Beef Exports

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## Abstract

**Irish beef exports illustrate the tension between economic benefits and environmental sustainability in the global food system. While exports support rural livelihoods and national trade revenue, they rely on energy-intensive cold chains and contribute to high greenhouse-gas emissions, land-use pressures and equity concerns. This study proposes an integrated shipping-and-ageing intervention that reconfigures maritime logistics as a site of controlled maturation and circular by-product management. In the redesigned system, beef is slaughtered and inspected in approved land-based plants, then loaded into shipboard ageing rooms where temperature, humidity and airflow are actively controlled and continuously monitored throughout the voyage. By shifting part of the maturation period from static cold stores to voyage time, the intervention aims to reduce land-based refrigeration, minimise handling stages, and improve traceability. The analysis also highlights governance risks—including rebound effects from efficiency gains—and argues that any logistics savings must be coupled to value-based quota or emissions-cap mechanisms and to an internationally recognised certification scheme for mobile processing units to avoid regulatory loopholes. Overall, the intervention is framed as one component of a broader transition strategy that also requires dietary change, regenerative agriculture and fair-trade governance.**

**Keywords**: Irish beef exports, cold chain, maritime logistics, sustainability intervention.

## 1 Introduction

Irish beef exports illustrate how global food trade can create economic value while driving disproportionate climate and land-use impacts [1, 2]. Recent studies further emphasize that global meat trade remains carbon-intensive due to entrenched cold-chain logistics and volume-driven models. The prevailing model depends on emission-intensive cold chains and under-valorised slaughter by-products, adding costs without fully realising the value of long-distance logistics. This portfolio maps the current Ireland-to-importer beef food system, analyses its sustainability challenges, and proposes an integrated shipping and ageing system that turns voyage time into controlled maturation and circular by-product use [3]. It then critically reflects on how far this intervention could realign traded beef with net-zero and planetary-health goals.

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## 2 Mapping the Irish Beef Export System

As illustrated in Figure 1, beef production is globally dispersed, with Ireland contributing a small but export-focused share. These exports rely on tightly coordinated cold-chain logistics: cattle are slaughtered and portioned, moved through cold stores, and shipped in refrigerated containers to importing regions, before distribution to retailers and consumers. Figure 2 further maps these sequential stages and highlights the key actors involved—including farmers, processors, hauliers, shipping companies, port authorities, regulators in both jurisdictions and powerful retail and food-service chains.

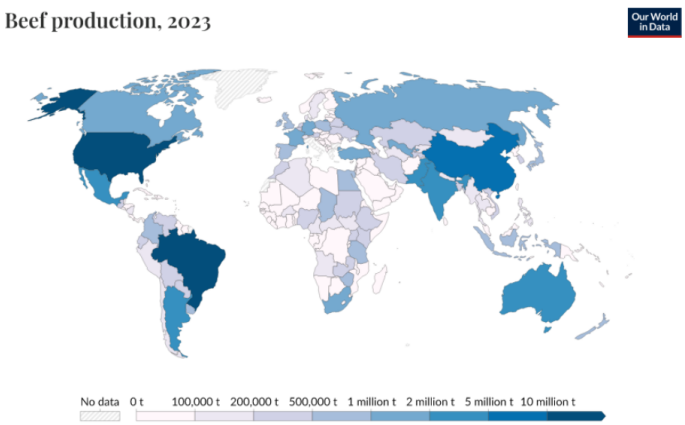


**Figure 1.** World map of beef production in 2023, showing highest output in the Americas, China and Australia [6].

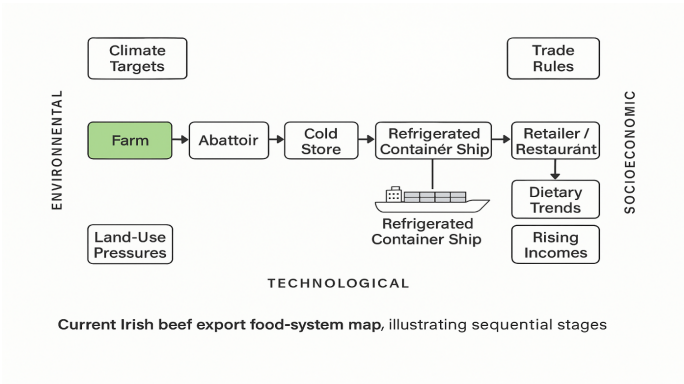


**Figure 2.** Current Irish beef export chain from farm to consumer, showing environmental, technological and socioeconomic drivers acting along the chain.

There are several forces that determine the operations of this system. On the environmental side, climate goals and land-use stress impede the future of ruminant livestock, and cold storage and long-distance sea transport cause additional emissions. Beef exports contribute to rural livelihoods and national trade revenue socio-economically, while also driving increases in incomes and status consumption in importing markets, sustaining demand for high-quality Irish beef. Trade is politically controlled by trade agreements, food safety, and animal welfare regulations that control the movement of products. Technologically, the efficiency in cold-chain and logistics in shipping can affect the feasibility and cost. Sustainability-planning viewpoint can be used to place this intervention in these broader frameworks and forces instead of an individualized technical solution [5, 10].

## 3 Sustainability challenges: climate, land, diets and equity

Irish beef exports embody several intertwined sustainability challenges. Per kilogram of protein, beef generates far higher greenhouse-gas emissions than plant-based sources, driven by enteric methane, nitrous oxide from fertiliser use and carbon dioxide from feed production, cold storage and long-distance shipping [2]. The refrigeration stage alone accounts for a significant portion of emissions in global meat supply chains [11], highlighting the urgency of rethinking cold-chain logistics in export systems. As illustrated in Figure 3, global beef and cattle herd sizes remain substantial-a scale that underpins persistent land-use pressures, feed-crop demand, and associated risks of habitat conversion and biodiversity loss.

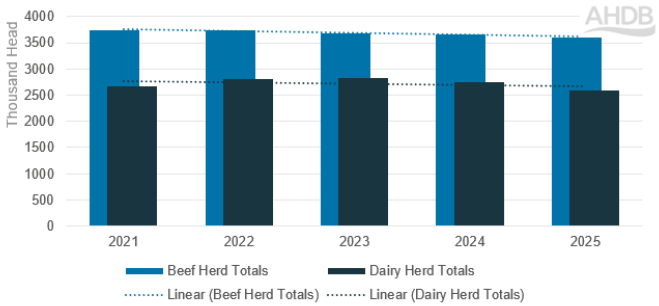


**Figure 3.** Beef and dairy herd totals in Great Britain, 2021–2025 (thousand head), showing a gradual decline in cattle populations that continues to contribute to land-use pressures and sustainability challenges [7] (Source: AHDB cattle and dairy population data).

Irish beef typically occupies a premium, status-associated niche in urban diets of importing regions. It is marketed in restaurants and high-end retailers as a symbol of quality, reinforcing consumption patterns that favour meat-intensive diets. It is uncomfortable in conjunction with planetary health diets that recommend a significant reduction of ruminant meat consumption and a transition to a variety of plant-based foods in order to operate within

climate and ecological boundaries [2].

Socio-economically, the current model generates export revenue and supports rural livelihoods in Ireland, yet farmers remain dependent on a small number of powerful processors and retailers that capture a disproportionate share of value. In importing countries, affluent consumers gain access to premium imported beef, while local producers may face intensified competition or be relegated to lower-value market segments. Urban sustainability research highlights how such flows can entrench inequalities in who benefits from, and who bears the environmental costs of, global food trade [4].

From a sustainability-planning perspective, this configuration represents a form of carbon- and infrastructure "lock-in". Investments in static cold stores, long-term contracts and established trade relationships make it difficult to align the system with net-zero trajectories without rethinking where emissions occur, how value is created and how interventions can shift both production and consumption pathways [5].

## 4 Proposed intervention

The proposed intervention re-engineers the export chain so that long-distance shipping becomes a site of value creation and mitigation rather than a passive, emission-intensive link. In the redesigned system, cattle are slaughtered and inspected in approved land-based plants, and carcases or primal cuts are transferred into sealed, shipboard ageing rooms on a specialised vessel. Ageing conditions are maintained within validated set points (temperature, relative humidity and airflow) using a dedicated HVAC system, with continuous sensor logging and alarms to ensure that each lot follows an equivalent maturation profile during the voyage. By using voyage time for controlled ageing, beef can arrive at the importing port already matured and ready for portioning and distribution, thereby reducing reliance on prolonged land-based cold storage and repeated handling. Such integrated approaches align with emerging strategies to decarbonise cold chains through logistics optimisation and system redesign [11].

To address the variability introduced by the marine environment (e.g., vessel vibration, pitch and roll), the ageing rooms are designed as mechanically decoupled modules with vibration-damped racking, shock-absorbing mounts and real-time motion sensing. Operationally, the quality system treats ship motion as a controlled variable: vibration and temperature/humidity excursions are recorded alongside product identifiers, and the ageing programme is validated through pilot voyages using microbiological limits, pH and sensory/texture outcomes as acceptance criteria. Redundancy (backup power and refrigeration capacity) and pre-defined corrective actions are embedded within the vessel HACCP plan to maintain product consistency and safety.

The intervention also explicitly manages the potential 'cold-chain gap' between the slaughter plant and the ship. Carcases/cuts are pre-chilled on land, transported to the loading port in refrigerated vehicles with sealed doors and continuous time–temperature logging, and transferred through a pre-chilled dockside handling area to minimise exposure. The shipboard ageing rooms are pre-cooled before loading, and loading is scheduled to keep any out-of-control temperature exposure to brief, auditable minutes rather than hours. This creates an end-to-end documented cold chain up to the point where shipboard ageing begins. The ship also functions as a mobile hub for circular resource management, but with clear operational boundaries. On board, slaughter by-products are segregated, labelled and held under controlled refrigeration or freezing in sealed containers to prevent cross-contamination and odour release. Full-scale rendering is not assumed to occur at sea; instead, the ship enables higher-quality capture and preservation of animal by-products so that they can be discharged at port to licensed, land-based rendering and treatment facilities operating under regulated ABP standards [8]. Where limited on-board processing is considered (e.g., size reduction or stabilisation), it must be enclosed, low-odour and compatible with containerised space and energy constraints, with appropriate filtration and waste-handling controls. This interpretation aligns the intervention with circularity research that emphasises by-product valorisation through integrated but regulated processing pathways [12].

The ship also functions as a mobile hub for circular resource use. Industry cross-sections of container vessels (Figure 4) illustrate how existing decks and holds can be repurposed as controlled-ageing rooms, chilled by-product storage and space for refrigerated return cargo. This aligns with recent research advocating for the valorization of slaughter by-products through integrated processing pathways to enhance resource efficiency and reduce waste [12].

Contemporary rendering processes convert raw slaughter by-products into value-added outputs such as rendered fat, protein meal and treated wastewater, illustrating the circular pathways that beef by-products from the integrated vessel could follow. These steps in size reduction, separation and quality assured processing also demonstrate how environmental responsibilities are transferred to specialised downstream processors operating under regulated ABP standards [8].

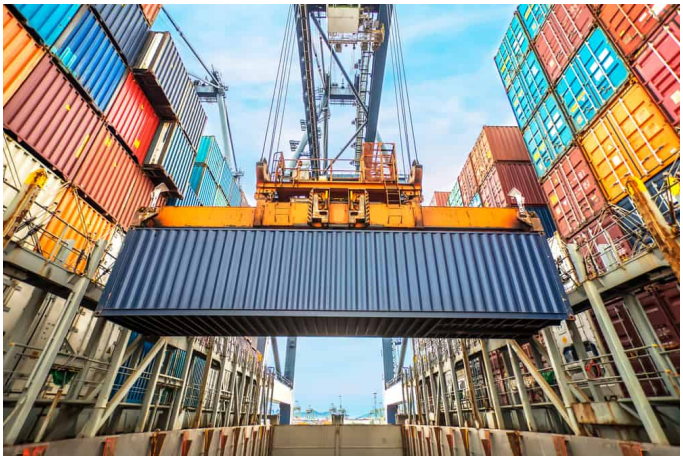

**Figure 4.** Container loading operation illustrating cold-chain logistics and maritime transport infrastructure underpinning long-distance beef exports.

The design is focused on governance, traceability and rebound prevention. Food safety, animal welfare and inspection requirements must be identical to—or stricter than—current practice, with veterinary supervision at slaughter and during loading. Each consignment is linked to a farm of origin, processing conditions, verified cold-chain records and an ageing profile through a digital traceability system. Critically, any logistics efficiency gains should not be allowed to translate into higher absolute volumes of methane-intensive exports. The intervention therefore needs an explicit governance mechanism—such as value-based export quotas, intensity-based caps linked to verified methane performance, or a sectoral emissions budget—so that value can rise without volumes rising. Following sustainability-planning principles, exported beef is repositioned as a high-quality, lower-volume product consumed alongside a progressive shift towards more plant-based diets in importing cities [2, 5]. The aim is to sustain farm incomes through value rather than volume, while relieving pressure on climate and land systems.

The design is focused on governance and traceability. Food safety and other animal welfare requirements should be identical or higher than the current requirements, and veterinary supervision is required at the slaughter area and when loading. Each consignment is associated with a farm of origin, processing conditions and ageing profile by a digital traceability system. Following the sustainability-planning recommendations, the intervention also reposition exported beef as a high-quality and lower-volume addition to the diets, alongside a progressive move towards more plant-based food in the cities of importation [2, 5]. The idea behind this less but better positioning is to sustain the incomes of farmers using value and not volume, and to relieve climate and land systems pressure.

## 5 Vision of change and critical reflection

If implemented at scale by 2035–2050, the integrated shipping and ageing system could alter the trajectory of Irish beef exports. Under the intervention scenario, the integrated shipping and ageing system would lower emissions per tonne of exported beef by reducing land-based cold storage, minimising handling stages and improving by-product utilisation through circular pathways. Long-term food-system outcomes are shaped by drivers such as population, income, diet and land use, reinforcing the need to position exported beef as a premium, transparently aged product rather than maximise volume. In importing cities, smaller quantities of high-quality beef consumed alongside more plant-based foods could modestly support planetary-health goals while sustaining or increasing farm income through higher value per animal.

Nevertheless, a critical sustainability viewpoint brings out significant shortcomings and governance requirements. First, the intervention still centres on a high-impact product; without parallel demand-side measures, absolute emissions from trade could remain incompatible with climate targets, even if emissions per tonne fall [10]. Second, improved efficiency can create rebound effects if lower logistics costs encourage greater trade volumes; this reinforces the need for binding governance instruments (e.g., value-based quotas or emissions caps) that explicitly prevent absolute volume growth while allowing value creation. Third, the complexity of overlapping jurisdictions (EU rules, flag-state regulation and destination-country controls) can create enforcement gaps. To avoid regulatory loopholes, an internationally recognised certification standard for

the 'mobile processing unit' is required—covering design, hygienic zoning, HACCP/food-safety management, auditability, data logging and port-state inspection protocols—supported by mutual recognition arrangements between flag and destination authorities. Finally, investing in specialised vessels risks locking capital into a carbon-intensive sector unless accompanied by clear transition plans, monitoring frameworks and transparent reporting [13]. Moreover, the success of such an intervention depends not only on technical feasibility but also on consumer acceptance and willingness to pay for premium, traceable beef. Cross-country studies indicate that consumers increasingly value transparency and sustainability narratives in meat products, although preferences depend on cultural context and trust in certification systems [14]. Therefore, technical innovation must be coupled with robust governance, certification and communication to end consumers.

Nevertheless, a critical sustainability viewpoint brings out significant shortcomings. First, the intervention continues to focus on high-impact product: unless there is a parallel focus on decreasing the aggregate demand on ruminant meat, absolute emissions in the trade might continue to be incompatible with demanding climate targets. Transitioning towards sustainable livestock systems requires not only technological innovation but also shifts in consumption patterns and dietary preferences [9]. Second, the complexity of regulations (i.e., EU rules, flag-state regulation, and destination-country regulation) may introduce governance gaps or lack of power balance, in case large logistics companies become disproportionately influential when it comes to setting standards and contracting outcomes [4]. Third, improved efficiency might generate rebound effects if lower logistic costs encourage greater trade volumes. Finally, global trade patterns are path-dependent; investing in specialised vessels risks locking capital into a carbon-intensive sector unless accompanied by clear transition plans and monitoring frameworks [13]. Moreover, the success of such an intervention depends not only on technical feasibility but also on consumer acceptance and market willingness to pay for premium, sustainably produced beef. Recent cross-country studies indicate that consumers increasingly value transparency, traceability, and sustainability narratives in meat products, yet these preferences are mediated by cultural contexts and trust in certification systems [14]. Therefore, alongside technical and governance innovations, efforts to communicate the value proposition of integrated shipping-and-aging systems to end consumers will be crucial.

The integrated shipping-and-ageing system reconfigures Irish beef exports by turning voyage time into a site of controlled maturation, reducing reliance on land-based cold storage and improving the capture and regulated valorisation of slaughter by-products. By explicitly managing shipboard ageing variables (temperature, humidity, airflow and motion), closing potential cold-chain gaps during port transfer, and embedding digital traceability, the intervention aims to improve product consistency while reducing some logistics-related energy use. However, it cannot be treated as a standalone sustainability solution. To avoid rebound effects and governance loopholes, logistics efficiencies must be coupled to binding value-based quotas or emissions-cap mechanisms and to an internationally recognised certification scheme for mobile processing units. The intervention is therefore best understood as one component within a wider transition strategy that must also encompass dietary change, regenerative production and fairer global trade governance.

## 6 Conclusion and implications

The integrated shipping and ageing system reconfigures Irish beef exports by turning voyage time into a site of controlled maturation, reducing reliance on land-based cold storage and improving the circular use of slaughter by-products. By embedding robust governance and traceability, and positioning exported beef as a high-quality, lower-volume product, the intervention seeks to ease some of the climate, land-use and equity pressures associated with long-distance meat trade. It is not a complete solution, but one component of a wider sustainability plan that must also encompass dietary change, regenerative production and broader policy and governance reforms in global food systems.

## Data Availability Statement

The data supporting this study are publicly available from the cited references and online sources (e.g., Our World in Data, AHDB).

## Funding

This work was supported without any funding.

## Conflicts of Interest

Tianchang Zou served as an Associate Editor of the *Agricultural Science and Food Processing* at the time of manuscript submission. To ensure the integrity of the peer-review process, Tianchang Zou was not involved in the editorial handling, peer review, or decision-making process for this manuscript, which was handled independently by another editor. The remaining authors declare no conflicts of interest.

## AI Use Statement

The author declares that no generative AI was used in the preparation of this manuscript.

## Ethical Approval and Consent to Participate

Not applicable.

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