PRESERVATION, COLD-CHAIN MANAGEMENT AND CIRCULAR-ECONOMY STRATEGIES FOR REDUCING FOOD WASTE IN THE REFRIGERATED MEAT SECTOR: A REVIEW

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Abstract

Meat is perishable and resource-intensive, so its loss and waste carry a disproportionate economic and environmental cost. This narrative review of the scientific and official literature (FAO, Eurostat, WOAH) examines how preservation and packaging, cold-chain management and circular-economy strategies reduce waste of refrigerated meat, and at what cost. Meat shows a global loss rate of 14.0% before retail, and in the EU about two-thirds of meat waste arises at consumption. Packaging extends chilled shelf life from 3–5 days to up to 25 days, but retail simulations indicate that it pays back only when its cost is lower than the waste it prevents, whereas cold-chain efficiency measures are repaid within 3–30 years. By-products (half to two-thirds of live weight) offer a circular route for the unavoidable fraction. The originality lies in linking technical performance to economic viability across these strategies, showing that stage-specific, cost-aware combinations are needed.

Key words: *refrigerated meat, food waste, cold chain, preservation, circular economy*

INTRODUCTION

Food loss and waste (FLW) is one of the most persistent inefficiencies of contemporary food systems. Approximately one-third of all food produced for human consumption, close to 1.3 billion tonnes each year, is lost or wasted between the field and the plate [1], at an estimated economic value approaching US$1 trillion and social/environmental costs of up to US$2.6 trillion when land, water and climate externalities are included [2]. In 2022 alone, close to 13% of food was lost before reaching retail and a further 19% of food available to consumers was wasted at retail, food-service and household level [3]. Beyond the direct economic cost, this waste squanders the land, water, energy and labor invested in production and is responsible for close to 8–10% of total anthropogenic greenhouse gas (GHG) emissions [4, 5]. Within this broader problem, animal-origin foods, and meat in particular, occupy a distinctive position. Unlike discarded cereals, fruits or vegetables, which mainly represent lost agricultural inputs, wasted meat embodies feed, water, veterinary care, land and, ultimately, an animal's life, so its loss carries a disproportionately large environmental footprint together with ethical and animal-welfare implications [6]. Recent estimates indicate that close to 20% of global beef production and 10–12% of pork and poultry production are lost somewhere along the supply chain, at a time when global demand for animal protein is projected to rise by a further 14% by 2030 [6].

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Refrigeration is central to this problem and, at the same time, to its solution. The cold chain, understood as the unbroken sequence of temperature- and humidity-controlled conditions from farm and abattoir to processing, distribution and retail, is what makes it possible to keep a highly perishable product such as fresh meat safe and marketable for more than a few hours [4]. Where the cold chain is absent, interrupted or poorly managed, meat is exposed to accelerated microbial growth, lipid oxidation and sensory deterioration, all of which shorten shelf life and increase the probability that a product is discarded before it is consumed [7]. Where the cold chain functions well, and where it is reinforced by modern packaging and monitoring technologies, meat's shelf life and marketability can be extended substantially, directly reducing the volume of product that becomes waste [6, 7].

The purpose of the present review is to synthesize the current scientific and institutional evidence on food loss and waste in the refrigerated meat sector, with four specific objectives. First, to quantify, using FAO, Eurostat and WOAH data alongside peer-reviewed literature, the scale and distribution of meat losses along the supply chain, from primary production to household consumption. Second, to critically evaluate the preservation interventions that have been proposed or demonstrated to reduce these losses, namely refrigeration and cold-chain management and conventional, active and intelligent packaging, building on our recent review of preservation and packaging strategies for refrigerated meat [7], and to relate the performance of each solution to the magnitude of waste it prevents. Third, because packaging and cold-chain upgrades are investment decisions and not only technical ones, to examine the economic dimension of these interventions, their cost relative to the value of the product and losses they protect, and the conditions under which they are economically justified. Fourth, to examine the behavioral, policy and circular-economy dimensions of meat waste prevention, including national evidence from Romania.

The research hypothesis underlying this synthesis is that meat FLW cannot be addressed by any single intervention acting in isolation; rather, measurable reductions require the coordinated deployment of cold-chain infrastructure, packaging innovation, consumer-facing information (notably date labeling) and circular-economy valorization of unavoidable by-products, calibrated to the specific loss profile of a given region or supply-chain stage. Divergent findings in the literature, for instance regarding whether shortening supply chains or upgrading refrigeration yields greater loss reduction [4], are highlighted and discussed rather than resolved uncritically, since the appropriate strategy depends strongly on regional infrastructure and the stage at which losses actually occur. The review is intended to be accessible to readers working outside food science, including policy-makers and agricultural economists, by consistently relating technical findings back to their practical implications for reducing meat waste.

MATERIAL AND METHOD

This paper follows a narrative-review methodology appropriate to synthesizing a heterogeneous, rapidly evolving body of literature spanning food science, environmental science, consumer behavior and policy. The evidence base comprises 54 peer-reviewed journal articles, book chapters, a doctoral thesis and official technical reports published between 2013 and 2026 in internationally indexed journals (including *Sustainability*, *Foods*, *Agriculture*, *Meat Technology*, *Environmental Research Letters*, *Frontiers in Sustainable Food Systems*, *Frontiers in Microbiology*, *Environmental Science & Technology*, *Journal of Cleaner Production*,

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Journal of Dairy Science, *Journal of Enterprise Information Management*, *PLoS ONE*, *Nature Food*, *Energies*, *Metabolites*, *Proceedings of the Nutrition Society* and the *Animal & Food Sciences Journal Iasi*), selected for direct relevance to food loss and waste, meat and animal-origin food supply chains, cold-chain and refrigeration technology, packaging science, consumer behavior toward perishable foods, circular-economy valorization of by-products, and food-security or waste-reduction policy, together with national-level studies from Romania and other Central and Eastern European countries.

Inclusion criteria were: (i) publication in a peer-reviewed journal, an academic thesis, or an official institutional report; (ii) explicit treatment of food loss/waste, meat supply-chain losses, refrigeration/cold-chain performance, meat packaging, or consumer/policy responses to food waste; (iii) availability of quantitative or clearly documented qualitative findings; and (iv) publication in English or Romanian. Sources limited to non-meat commodities without transferable methodological relevance, and non-peer-reviewed opinion pieces, were excluded; where a source addressed food waste broadly rather than meat specifically, it was retained only where its findings were judged directly transferable to the refrigerated-meat case (for instance, consumer date-labeling behavior or packaging-driven shelf-life effects demonstrated for dairy).

To complement the peer-reviewed literature with independently verifiable, up-to-date quantitative benchmarks, three official statistical sources were consulted directly: the Food and Agriculture Organization of the United Nations (FAO), through its Food Loss Index reported against Sustainable Development Goal indicator 12.3.1 [8]; the European Union's statistical office (Eurostat), through its 2023 food-waste-generation accounts reported under the EU Waste Framework Directive [9]; and the World Organisation for Animal Health (WOAH), through its *State of the World's Animal Health* reporting on production losses attributable to animal disease [10]. Values extracted from these sources are presented in Figs. 1 and 2, and no raw datasets were re-analyzed statistically beyond descriptive aggregation, consistent with the scope of a narrative review.

Synthesis followed a thematic rather than a study-by-study approach: findings were grouped according to the stage of the meat supply chain at which they primarily apply (primary production and slaughter, processing, distribution/retail, and consumption), and according to the type of intervention discussed (refrigeration/cold-chain management, packaging technology and its economic viability, consumer/behavioral measures, demand-side and circular-economy measures, and digital/policy measures), consistent with recommended practice for narrative and scoping reviews in this field [11]. The remaining figures (Figs. 3–8) and tables are based on values reported in the peer-reviewed sources indicated in their captions.

RESULTS AND DISCUSSION

Defining and quantifying food loss and waste in the meat sector

There is no single, universally applied definition of food loss and waste. FAO's Global Initiative on Food Loss and Waste Reduction defines food loss as the decrease in mass or quality of food throughout the supply chain, with food waste treated as the portion of that loss occurring at the retail and consumption stages [12]. Definitions diverge across stakeholders in scope (whether inedible parts are included), timing, and accounting perspective, which complicates cross-study comparison and is itself identified in the literature as an obstacle to designing effective reduction policies [1, 12].

Notwithstanding this definitional heterogeneity, the broad scale of the problem is consistent across sources. According to

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FAO's Food Loss Index (SDG indicator 12.3.1), the global food loss rate from post-harvest through wholesale/processing stood at 13.3% in 2023, essentially unchanged from 13.0% in 2015, meaning the world has made no measurable aggregate progress on this target despite it being a stated priority [8]. Loss rates vary markedly by commodity (Fig. 1): fruits and vegetables show the highest rate, at 25.4% in 2023 (23.2% in 2015), followed by meat and animal products at 14.0% (13.9% in 2015), roots, tubers and oil-bearing crops at 12.3% (12.6%), and cereals and pulses at 8.4% (8.5%) [8]. For meat, the loss rate has therefore remained practically unchanged between the two reference years. A similar ordering is reported for the downstream, retail-to-consumer segment of the chain, where FLW shares of around 20% for meat and poultry, 35% for fish and seafood and up to 45% for fruits and vegetables have been documented [3, 13], while an earlier synthesis based on US meat-waste valuation placed the annual cost of meat losses at over US$83 billion [14]. Regionally, sub-Saharan Africa records the highest post-harvest losses (23.0%), while Northern America and Europe report the lowest (10.0%), a pattern consistent with the infrastructure-dependent nature of many losses, discussed further below [8].

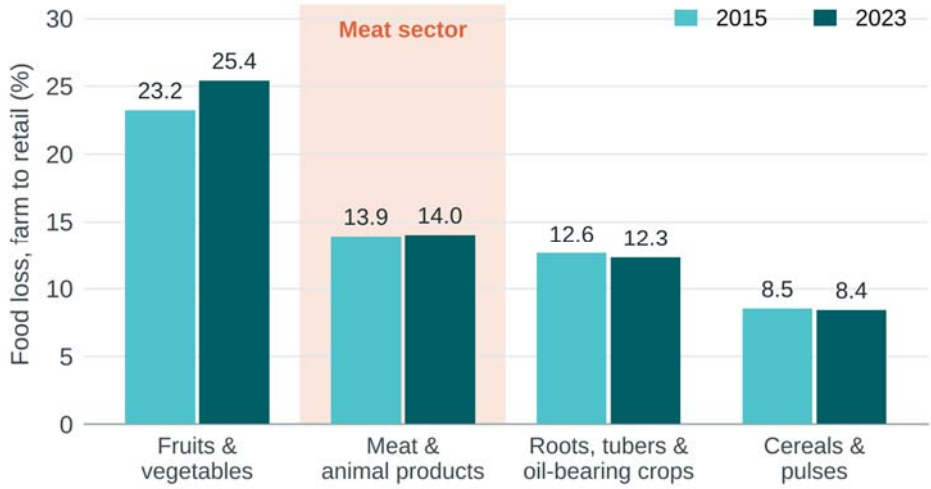


Fig. 1 FAO Food Loss Index by commodity group, 2015 and 2023: loss rate from post-harvest to the retail stage (%). Data: FAO Sustainable Development Goals Data Portal, SDG indicator 12.3.1 [8].

At the level of the individual consumer, Eurostat's most recent reporting (reference year 2023) puts total EU food waste generation at 58.2 million tonnes, or approximately 130 kg per inhabitant per year [9]. Disaggregated by sector, households account for the largest share (53%, 69 kg/inhabitant/year), followed by processing and manufacturing (19%, 24 kg), food service and restaurants (11%, 14 kg), primary production (10%, 12 kg) and retail/distribution (8%, 10 kg) (Fig. 2) [9]. It should be noted that, at the time of the 2023 reporting cycle, complete data for several Member States (Romania, Bulgaria, Spain and Lithuania) were still pending, so EU aggregates relied on the latest available national estimates, a data gap that itself illustrates the measurement challenges affecting FLW policy in parts of the Union [9].

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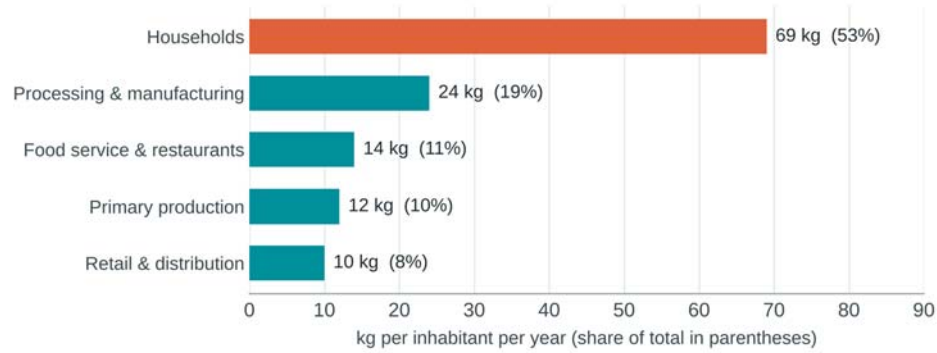


Fig. 2 Food waste generation in the EU by sector of activity, reference year 2023 (kg per inhabitant per year; share of the total in parentheses). Data: Eurostat, Waste Statistics – Food Waste [9].

A further, often overlooked, contributor to meat losses lies upstream of the classical supply-chain stages: animal disease. WOAH estimates that approximately 20% of global livestock production is lost to animal disease every year, at an estimated cost to producers of around US$300 billion, encompassing mortality, reduced productivity and carcass condemnation at slaughter [10]. Complementing this, Karwowska et al. [15] report that carcass rejection at the slaughter stage, driven by sanitary defects or processing inefficiencies, typically removes a further 2–5% of throughput, a figure corroborated by Bytyqi et al. [6]. These upstream, health- and safety-driven losses are structurally different from the retail- and consumer-stage waste that dominates volumetrically in developed regions (see next section), and they call for a distinct policy toolkit centered on veterinary infrastructure and animal-health investment rather than on cold-chain or packaging interventions.

Distribution of losses along the meat supply chain

The meat supply chain loses product at every stage, but the relative contribution of each stage differs sharply between industrialized and developing regions. Drawing on EU FUSIONS mass-flow accounting, Karwowska et al. [15] estimate that 23% of all meat entering the EU food supply chain (production plus imports minus exports and non-food uses) is ultimately lost or wasted, and that within this total, the consumption stage (households and food service combined) accounts for 64.5%, manufacturing for 20%, distribution for 12%, and primary production/post-harvest for only 3.5% (Fig. 3) [15]. A closely converging estimate places overall meat-sector loss at 23% of production with an almost identical stage-wise split (64% consumption, 20% manufacturing, 12% distribution, 3.5% production), against a backdrop of global meat output of roughly 252.6 million tonnes and a livestock sector responsible for about 14.5% of anthropogenic GHG emissions [16]. A larger, systematic review of animal-origin FLW similarly concludes that around one-fifth of the roughly 263 million tonnes of meat produced worldwide each year is lost or wasted, at a cost of US$750 billion to US$1.0 trillion, with meat and milk waste together accounting for 78% of the agricultural land wasted on discarded animal-origin food [17]. This pattern, in which losses concentrate toward the end of the chain, is characteristic of wealthier regions with high per-capita meat consumption and relatively robust upstream infrastructure [15]. By contrast, in developing regions, including North Africa, West and Central Asia, Latin America, and sub-Saharan Africa, most meat loss occurs

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at the production and storage stages, reflecting inadequate slaughter facilities, insufficient cold-chain penetration and disorganized logistics rather than consumer behavior [6, 15], a divide also confirmed by a broader food-waste-management review that links early-supply-chain losses in developing countries specifically to inadequate packaging, transport infrastructure and cooling, as against the retail- and consumer-stage concentration typical of developed markets such as the EU, where sector-level food waste is estimated at 53% households, 19% processing, 12% food service, 11% production and 5% wholesale/retail [18].

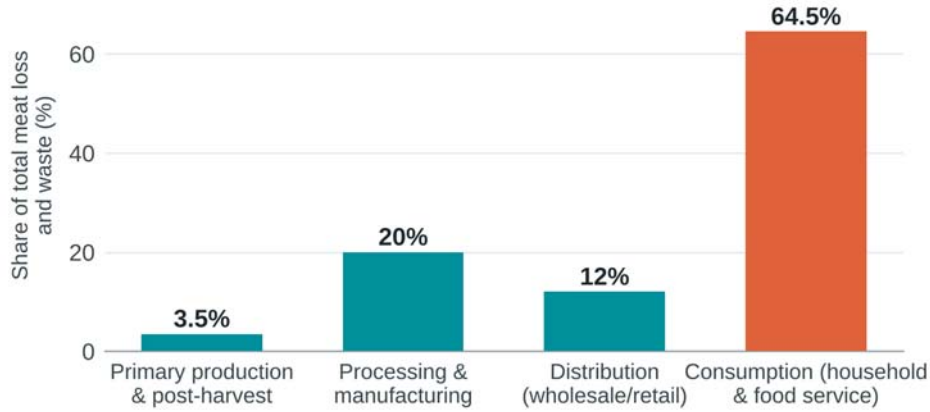


Fig. 3 Distribution of losses along the EU meat supply chain, as a share of total meat loss and waste (%). Based on EU FUSIONS mass-flow data reported by Karwowska et al. [15].

Meat's disproportionate environmental weight within FLW is confirmed by GHG-hotspot analysis: although bovine meat represents only about 0.7% of total global FLW mass, it accounts for 16.3% of FLW-associated GHG emissions worldwide, a share comparable to that of fruits and vegetables (16.8%), which account for about half of the FLW mass (Fig. 4), and this share rises to 44% of consumer-stage FLW-related emissions in North America and Oceania [19]. Complementing this mass/emissions asymmetry, a bibliographic review of food-system energy use estimates that beef-derived products generate on the order of 120 kg CO_2-eq per kg, that meat production alone accounts for close to 70% of total food-related land use, and that lamb and beef respectively require around 375 m² and 320 m² of land per kilogram, figures that place the meat sector's environmental stakes well above its share of FLW tonnage [5]. Colombani and Brunner [20] caution that meat loss and waste estimates derived indirectly from consumption and availability data (as most national and FAO estimates are) carry substantial uncertainty, since they depend on assumptions about edible-to-inedible ratios, cold-storage practices and reporting completeness that vary widely between countries; this reinforces the case, made independently by Vilariño et al. [1] and by Spang et al. [11], for more direct, harmonized measurement protocols such as the Food Loss and Waste Accounting and Reporting Standard.

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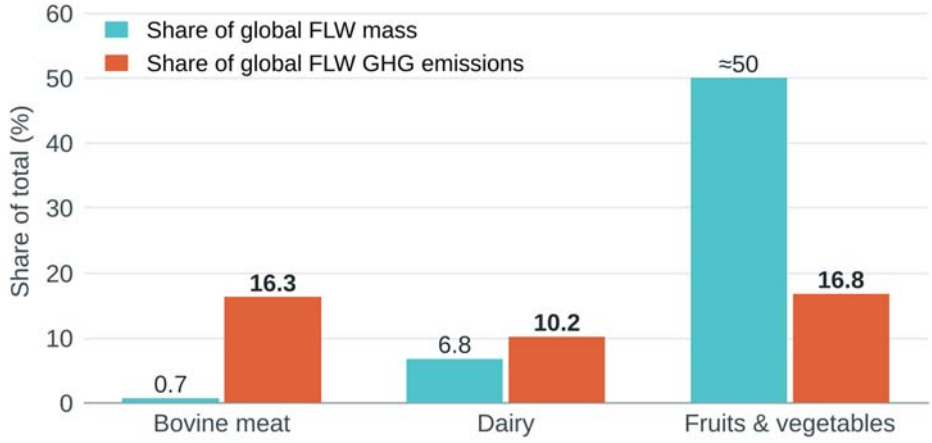


Fig. 4 Share of global food loss and waste (FLW) mass and of FLW-associated greenhouse-gas emissions for bovine meat, dairy and fruits and vegetables (%). Data: Guo et al. [19].

The central role of refrigeration and the cold chain

The cold chain is repeatedly identified in the literature as the single most consequential piece of infrastructure for meat loss prevention, precisely because meat's short intrinsic shelf life makes it disproportionately sensitive to temperature control failures relative to more storable commodities [4, 21]. Friedman-Heiman and Miller [4] developed a food-loss estimation tool spanning seven food types and seven world regions and estimated that poor cold-chain infrastructure could be responsible for up to 620 million tonnes of food loss globally, associated with 1.8 $GtCO_2$-eq of emissions annually; fully optimized cold chains could save over 100 million tonnes of fruit and vegetable loss in South and Southeast Asia alone and reduce GHG emissions from meat losses in industrialized regions by over 300 million tonnes CO_2-eq [4]. Fig. 5 maps the stages of the meat chain, the share of EU meat loss and waste generated at each of them, and the main measures discussed in the following sections. Importantly, however, the same study finds that cold-chain optimization is not a universal panacea: in already fully industrialized regions such as Europe, further refrigeration investment yields comparatively limited additional loss reduction, because cold-chain penetration is already high, whereas shortening and localizing supply chains ("farm-to-table" models) can, in some scenarios, save more food overall than an optimized but long cold chain [4]. This nuance is significant for policy design: it implies that refrigeration investment should be targeted preferentially at non-industrialized regions and at specific weak links (post-harvest handling, transportation, and processing/packaging) rather than applied uniformly, echoing findings from the Global Food Cold Chain Council's comparative analysis of cold-chain penetration [4].

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Fig. 5 Conceptual scheme of the refrigerated-meat chain: share of EU meat loss and waste by stage [15] and the main loss drivers and mitigation measures discussed in this review.

Davoudi et al. [21] similarly document two decades of advancement in cold-chain logistics, including "first-expire, first-out" predictive models for retail loss reduction and blockchain-supported cold-chain architectures for beef traceability, while also cautioning that cold-chain ruptures (fragmented versus integrated logistics) remain a persistent source of loss even in developed markets. At subzero temperatures specifically, Shafel et al. [22] note that while freezing halts microbial growth more completely than chilling, ice-crystal formation during freezing and thawing can degrade texture and juiciness, illustrating the quality/safety trade-offs inherent even within cold-chain technology choices. Freezing's practical benefit at the household level is corroborated by a UK survey-based study, which found that households using frozen food generated 47% less waste than with the equivalent fresh product category, and separately quantified EU pre-consumer meat waste at a very low 0.10–0.35% of production, confirming that upstream, cold-chain-served stages of the meat supply chain are already comparatively efficient and that most remaining opportunity lies further downstream, at retail and in the home [23].

Refrigeration also carries its own, often underestimated, energy and infrastructure cost. Space cooling and refrigeration together were responsible for roughly 4,400 Mt CO_2-eq of emissions in 2020, more than 10% of global GHG emissions, and the global cold-chain sector was valued at over US$160 billion in 2018 and has continued to grow at around 16% per year [5]. This same body of work catalogs concrete efficiency interventions directly applicable to meat cold chains, such as head-pressure control systems (up to 25% energy savings), routine refrigeration maintenance (10–20%

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savings), waste-heat recovery (10–45% of otherwise-wasted energy) and variable-speed drives (30–70% savings), indicating that reducing the cold chain's own footprint and reducing the meat losses it prevents can, and should, be pursued jointly [5]. A country-level illustration of what is at stake when cold-chain and processing losses are not controlled comes from Ukraine, where FAO-consistent stage-wise loss rates for meat (3.1% production, 0.7% storage, 5.0% processing/packaging, 4.0% retail, 11.0% consumption) were found to account for 72.0% of the national meat-consumption deficit relative to nutritional norms, underlining how closely food-loss reduction and food-security outcomes are linked in economies where cold-chain and processing infrastructure remain under strain [24].

Packaging technologies for refrigerated meat: conventional, active and intelligent systems

Because refrigeration alone does not eliminate microbial and oxidative deterioration, packaging has become an essential complementary layer of meat preservation. Our recent review [7] synthesizes this literature specifically for refrigerated meat and distinguishes conventional, active and intelligent packaging systems, each with characteristic trade-offs [7]. Conventional overwrap packaging, using oxygen-permeable film over expanded polystyrene trays, maximizes the bright red, oxymyoglobin-driven color that consumers associate with freshness, but its continuous oxygen exposure accelerates lipid oxidation and supports aerobic spoilage organisms, limiting shelf life to about 3–5 days [7]. Vacuum packaging (VP) removes oxygen entirely, suppressing aerobic spoilage and oxidation and extending chilled shelf life to approximately 10–14 days, at the cost of a purplish deoxymyoglobin color that can reduce consumer acceptance despite the meat's chemical stability [7]. Modified atmosphere packaging (MAP), using tailored $O_2/CO_2/N_2$ mixtures, can reconcile these objectives: elevated oxygen preserves color while carbon dioxide exerts a bacteriostatic effect, with balanced mixtures (roughly 20–40% O_2, 40–60% CO_2) extending shelf life to 14–21 days depending on the specific meat type and gas ratio [7]. Typical chilled shelf-life ranges for these formats are compared in Fig. 6.

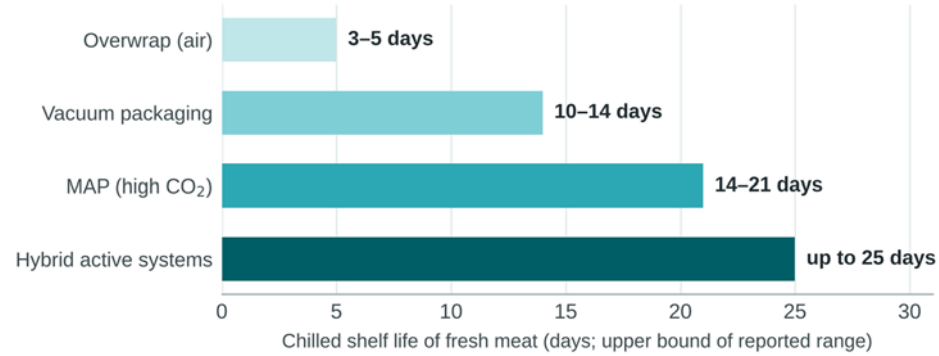


Fig. 6 Typical chilled shelf life of fresh meat under different packaging formats (days; upper bound of the reported range) [7]

Beyond these conventional systems, active and intelligent packaging represent the fastest-growing area of innovation. Active packaging incorporates oxygen scavengers, natural or synthetic antioxidants (such as rosemary extract), and antimicrobial agents (essential oils, organic acids, or, in emerging applications, TiO_2 nanocomposites) directly

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into the packaging matrix, allowing the package to interact with the product environment rather than acting only as a passive barrier [7]. Intelligent packaging, by contrast, does not alter the product environment but monitors it: time-temperature indicators record cumulative cold-chain exposure, gas sensors detect the volatile compounds associated with spoilage, and colorimetric freshness indicators (based on natural pigments such as anthocyanins or curcumin) allow visual, instrument-free assessment of product condition at any point in the chain [7]. Industrial case studies cited by Bytyqi et al. [6] report shelf-life extensions of up to 50% and food-waste reductions of nearly 40% where advanced active/intelligent packaging has been deployed commercially, while AI-driven dynamic-pricing systems linked to freshness data have demonstrated meat-waste reductions of up to 30% at retail.

It is worth noting that shelf-life extension through packaging does not automatically translate into less waste further down the chain. A Swedish dairy-sector case study found that even after the shelf life of chilled products was roughly tripled, several tonnes per year still never left production storage, because retailers required deliveries to retain a large share of remaining shelf life and longer-shelf-life products were consequently produced less often and held longer before dispatch [25]. Packaging format itself can also matter as much as shelf life: switching single-person households from larger to smaller milk containers cut spoilage from about 40 to 10 liters per year and lowered associated emissions by roughly a third, an intervention logic (right-sizing packaging to household consumption patterns) that is directly transferable to portioned refrigerated meat [26]. Table 1 summarizes the comparative performance and limitations of the main preservation and packaging methods discussed in the reviewed literature.

Notwithstanding these advances, our review identifies important gaps: economic evaluation of advanced packaging at industrial scale remains limited, methodological variability across studies (particularly those using natural extracts) complicates comparison, and consumer willingness to pay for innovative packaging is insufficiently documented [7]. These gaps are consistent with Bytyqi et al.'s [6] broader observation that regulatory uncertainty, high capital costs and uneven technology uptake, particularly in low- and middle-income countries, continue to constrain the real-world impact of otherwise promising preservation technologies.

Table 1 Comparative overview of refrigerated-meat preservation and packaging methods, typical chilled shelf life and principal limitations (compiled from [6, 7, 21])

Method	Mechanism	Typical shelf life (chilled)	Principal limitation
Refrigeration alone	Slows enzymatic and microbial activity	3–5 days	Does not halt psychrotrophic growth
Overwrap (PVC film)	Oxygen-permeable film, retail display	3–5 days	Rapid lipid oxidation; short turnover window
Vacuum packaging (VP)	Oxygen removal	10–14 days	Purplish color; anaerobe survival if the cold chain breaks
Modified atmosphere packaging (MAP)	Controlled O□/CO□/N□ mixture	14–21 days	Requires product-specific gas optimization
Active packaging (scavengers, antimicrobials)	Direct interaction with spoilage pathways	Up to 25 days (hybrid systems)	Cost; regulatory migration limits; sensory effects
Intelligent packaging (TTIs, sensors)	Monitoring and communication only	Not applicable (informational)	Sensor cost; calibration; no direct preservation effect

Note: PVC, polyvinyl chloride; TTI, time–temperature indicator; MAP, modified atmosphere packaging; VP, vacuum packaging.

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Economic dimensions of refrigerated-meat loss, waste and packaging interventions

Beyond its environmental and food-security costs, meat loss and waste represents a very large, directly quantifiable economic loss, and it is against this baseline that the economic case for packaging and cold-chain investment should be read. In the United States, the value of wasted meat has been estimated at roughly US$83 billion annually, with consumers responsible for about 35% of that loss and retailers for a further 5%, while wasted poultry alone was separately valued at approximately US$69 billion, again with consumers accounting for the largest single share (37%) [14]. At the retail and food-service level specifically, US surplus food was estimated to cost the economy US$473 billion in 2022, a year in which fresh meat and seafood made up a disproportionate share of retail surplus relative to their share of sales, given their perishability and higher value density [27]. A comparable European illustration comes from Italy, where fresh-meat waste of 0.45–0.50 million tonnes per year has been valued at €242–268 million in direct product losses, plus a further €435–481 million in the energy and water embedded in that wasted meat, a reminder that the economic cost of meat waste extends well beyond the shelf price of the discarded product itself [16]. These indicators are summarized in Table 2.

Table 2 Economic evidence on refrigerated-meat waste and on the cost-effectiveness of mitigation measures (compiled from [5, 14, 16, 27, 28])

Indicator	Value	Scope and source
Value of wasted meat	US$83 billion per year (consumers 35%, retailers 5%)	United States [14]
Value of wasted poultry	About US$69 billion per year (consumers 37%)	United States [14]
Surplus food at retail and food service	US$473 billion in 2022; fresh meat and seafood 13.6% of retail surplus; 72.5% of rejected items lost to spoilage or packaging damage	United States [27]
Fresh-meat waste	0.45–0.50 Mt per year, i.e., €242–268 million, plus €435–481 million in embedded energy and water	Italy [16]
Retailer waste, fixed vs. dynamic shelf life	1.87% → 1.33% (base case); 20.61% → 4.05% (5-day product)	Retail simulation [28]
Cold-chain efficiency measures	Payback within 3–30 years	Food-industry case data [5]

Note: Mt, million tonnes. Monetary values are those reported in the cited sources and are not adjusted for inflation or exchange rates.

Set against these losses, packaging and preservation technologies have a direct, quantifiable economic logic, though a more conditional one than "more technology, less waste" would suggest. A detailed retailer-level simulation of a meat supply chain found that replacing a fixed shelf life with a dynamically adjustable one, informed by real-time product-quality data of the kind intelligent packaging provides, consistently reduced both waste and stock-outs while increasing retailer profit compared with a fixed-shelf-life policy, and that combining a dynamic shelf life with price discounting of near-date stock reduced waste further still, in the best-performing scenarios more than halving retail waste relative to a conservative fixed-shelf-life baseline [28]. In the base case of that simulation, replacing a fixed with a dynamic shelf life lowered retailer waste from 1.87% to 1.33%, and for a product with a short, 5-day shelf life from 20.61% to 4.05%, whereas the benefit disappeared for a longer-lived, 10-day product (0.64% vs. 0.65%) (Fig. 7) [28]. The same model shows, however, that the

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profitability of intelligent packaging is conditional on its own cost: a simple, cheap freshness indicator increased profit, but a more sophisticated, more expensive sensor could reduce profit whenever its cost outweighed the extra waste it prevented [28]. This is echoed by our packaging review [7], which notes that multilayer active-packaging systems are generally more expensive than conventional formats and that this added cost is best justified in long or complex distribution chains, where the resulting shelf-life extension has the most value, while advanced biosensor-based intelligent packaging in particular still requires substantial cost reduction before industrial-scale adoption becomes economically viable [7]. Complementing this retail-level view, the cold-chain efficiency interventions discussed earlier are reported to pay for themselves within three to thirty years depending on the specific measure, with average energy savings on the order of 61–166 tonnes of oil equivalent per intervention in the food-industry case data reviewed, indicating that, unlike some packaging upgrades, cold-chain efficiency investment is a comparatively low-risk economic proposition over a sufficiently long horizon, even before its waste-reduction benefits are counted [5].

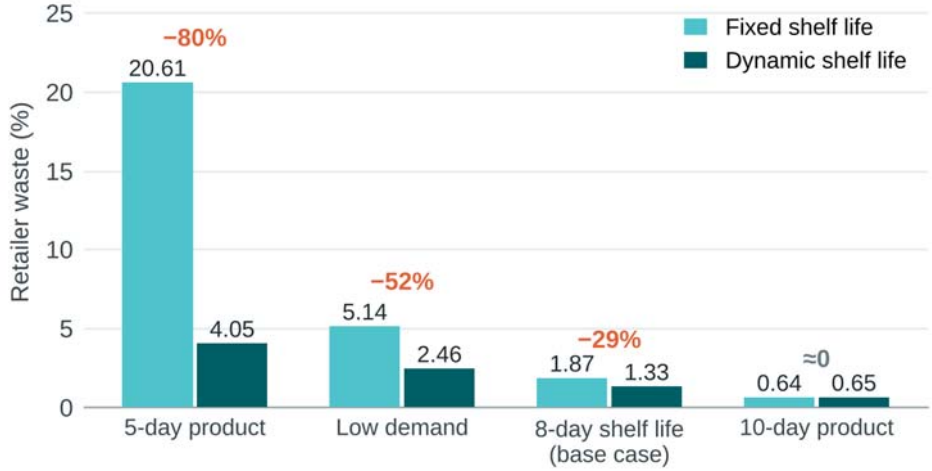


Fig. 7 Retailer waste of a fresh meat product under fixed and dynamic shelf-life policies in a simulated retail supply chain (%); relative changes calculated from the reported values. Data: Buisman et al. [28].

Taken together, this evidence reframes the choice of packaging and cold-chain technology as a cost-matching problem rather than a simple question of whether to adopt new technology. Because both under-investment, accepting avoidable spoilage that the loss figures above show to be economically substantial, and over-investment, in packaging whose cost exceeds the waste it prevents, are economically inefficient, the central implication of this evidence is that packaging and cold-chain interventions should be selected and priced against the specific value density, shelf-life sensitivity and distribution-chain length of the meat product in question, rather than adopted uniformly across a product range [5, 7, 28].

Consumer behavior, date labeling and household waste

Because consumption-stage waste dominates volumetrically in developed food systems (Fig. 3), consumer behavior deserves particular attention. A recurring finding across multiple independent studies is that consumers systematically misunderstand food date labels: Karanth et

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al. [29] report that most consumers, irrespective of educational attainment, cannot correctly interpret "best before" versus "use by" labeling and conflate quality indicators with safety indicators, resulting in food, including meat, being discarded well before it is actually unsafe to eat. Some consumers go further and treat any date on the label as marking the point after which a product becomes actively harmful, an interpretation that a food-security and safety review explicitly flags as a misreading with direct waste consequences [30]. Neff et al. [31], surveying U.S. consumers specifically about perishable dairy, found that 91% of respondents reported paying attention to date labels, yet the methods used to judge freshness were inconsistent and only loosely related to actual spoilage risk, with sensory assessment ("use my senses," 72%) outweighing reliance on any single printed date. A Polish household survey similarly found that "food expired" was cited by 74.9% of respondents as the main reason for discarding food, with meat and cold cuts making up 35.9% of wasted products (fourth, after fruits/vegetables, bread and dairy products), and confirmed only weak statistical association between waste behavior and demographic factors such as age or sex [32]. Farr-Wharton et al. [33] and Aschemann-Witzel et al. [34] similarly identify over-purchasing, poor meal planning, low tolerance for visual imperfection, and confusion over labeling terminology as recurring behavioral drivers of household food waste, while noting that willingness to pay for a perishable product declines measurably as it approaches its labeled date, an effect retailers can exploit through dynamic discounting to reduce retail-stage losses [28, 34].

A five-country EU project on consumer acceptance of "suboptimal" food, including items nearing or past their best-before date, found that such products were chosen far more often at home than in a simulated supermarket, that the discount required to make a near-date item acceptable rose sharply for perceived safety-relevant defects, and that this safety-related reluctance was reported to be particularly pronounced for perishable, risk-sensitive categories such as meat and fish; the same project found that price-reduction stickers on near-date items were highly effective at the retail level, with the great majority of discounted stock selling [35]. In a controlled behavioral study using an extended Theory of Planned Behaviour model, adding contextual factors such as food surplus, planning routines and hospitality-driven social norms raised the explanatory power for food-waste behavior from 20% to 35%, underscoring that surplus generated by social or seasonal eating occasions, not only individual attitudes, is a measurable driver of waste [36]. A broader synthesis of EU household food-waste research likewise identifies financial capacity, planning habits, and distrust of date labelling as recurring drivers and barriers, and reports EU consumers discarding on the order of 123 kg of food per person annually [37]. Diet quality itself interacts with waste: US dietary-intake modelling found that higher-quality diets were associated with significantly more food wasted by weight, including a meat and mixed-meat-dish share of about 13.5% of total consumer waste, because nutrient-dense fresh categories such as fruits, vegetables and animal-origin foods are also the most perishable [38]. Finally, the COVID-19 pandemic offered a natural experiment in consumer behavior: increased home meal-planning during lockdowns reduced food waste in many studies, while panic buying and the rapid growth of food delivery and online grocery shopping had mixed or negative effects, notably increasing packaging waste, and household food waste's share of the global total was estimated to have risen to around 61% during this period [39].

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These findings collectively support the case, made explicitly by several of the reviewed sources, for standardizing and simplifying date-labeling systems and for pairing such standardization with consumer education, since technological interventions upstream (better cold chains, better packaging) cannot fully compensate for information failures at the point of consumption [29, 33]. Intelligent packaging's freshness indicators, discussed above, represent one technological response to this specific problem, since they substitute an observed physical/chemical state for a fixed printed date [7].

Meat demand, alternatives and the underused by-product fraction

A distinct but complementary line of literature addresses meat FLW from the demand side, asking whether reducing meat consumption itself, or making fuller use of the parts of the animal not conventionally eaten, can reduce the resource and waste burden associated with meat. Survey evidence from the Netherlands shows a substantial and growing share of "flexitarian" consumers reducing meat-eating frequency (with serious meat-reducers rising to over 40% of respondents in one wave), yet average per-capita meat consumption barely moved over the same period, a "meat paradox" the authors attribute to possible portion-size compensation and that they flag as needing further study [40]. This is consistent with a broader European policy review identifying reduced meat and dairy consumption as among the most effective individual and institutional levers for lowering the environmental footprint of diets, given that meat and meat products alone were estimated to contribute 9–14% of total EU-25 food-related GHG emissions, and with its finding that avoidable household food waste (UK and Germany both reporting roughly two-thirds of discarded food as avoidable) compounds, rather than substitutes for, the environmental cost of that consumption [41]. At EU and global scale, livestock production is responsible for a large share of agricultural GHG emissions and land use, and yet the non-meat components of the carcass, offal, bones, hide and similar fractions, can represent more than half of live weight and remain substantially under-exploited in Western markets because of consumer disgust, unfamiliarity and regulatory constraints, despite campaigns promoting nose-to-tail consumption of organ meats [42]. Cross-country consumption data confirm this asymmetry starkly: annual per-capita offal consumption exceeds 50 kg in some Asian markets but remains below half a kilogram in others, illustrating that the "waste" status of edible by-products is culturally constructed rather than intrinsic to the product [43]. The same evidence base finds that global meat consumption is still projected to rise by roughly 14% by 2030, driven mainly by poultry, even as red-meat consumption declines in many high-income countries, so demand-side measures are best understood as complementing rather than substituting for supply-chain loss reduction [43].

On the technological side, comparative carbon-footprint data show that meat types differ substantially in resource intensity (from roughly 4–11 kg CO_2-eq/kg for poultry and pork up to 14–52 kg CO_2-eq/kg for beef and lamb), which is directly relevant to prioritizing which meat losses matter most for climate outcomes [44]. A national-level assessment for Austria estimated that fully preventing waste generated during meat processing could avoid up to 4.8 million tonnes of CO_2-eq annually, equivalent to about 6% of the country's total emissions, underscoring the climate relevance of processing-stage by-product recovery specifically [44]. Concrete valorization pathways reported in the literature include recovering functional proteins from otherwise-discarded processing streams (blood plasma, exudates, brine) to partially replace

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conventional protein in reformulated products, extracting usable protein fractions from waste meat using low-energy non-thermal processing, and converting animal by-products into biodiesel, biogas and heat/electricity via anaerobic digestion [44], with a wider catalogue of by-product uses, blood, hides, bones and glandular tissue converted into feed, gelatin, pharmacological inputs and leather, further illustrating how much of the "non-meat" carcass fraction already has established, if underused, commercial value [13]. Uptake of these pathways nonetheless remains constrained by consumer acceptance barriers, regulatory hurdles (including post-BSE restrictions on reusing processed animal by-products, which curtail how much of the roughly 100 million tonnes of annual EU food waste can currently be recycled to animal feed) and heterogeneous, high-moisture waste streams that complicate large-scale processing [13, 14].

Retail and food-service losses specific to meat

Retail and out-of-home food service constitute a distinct, meat-relevant loss point that sits between the supply-chain and household-consumption perspectives discussed above. A review focused specifically on this segment reports that meat, dairy and oilseed losses of around 20% are common globally at this stage, and attributes a large share of this to compromised cold chains, particularly in lower-income countries; in the United States, fresh meat and seafood alone accounted for about 13.6% of retail surplus food in a recent national accounting, and an investigation of rejected retail meat and seafood found that 72.5% of rejected items were categorized as losses due to spoilage or packaging damage, directly implicating cold-chain and packaging failure as the dominant retail-stage cause [27]. The same review catalogs mitigation technologies directly applicable to refrigerated meat retail, including RFID- and sensor-based temperature tracking, bio-responsive spoilage-indicating labels, and lowering retail display-case temperatures to extend shelf life, alongside donation pathways balanced against food-safety risk under a food-recovery-hierarchy framework [27].

At the food-service level, a large telephone survey of German hospitality and catering businesses found median meat-waste ratios of 1–5% of weekly purchases depending on business type, extrapolating to a national estimate of roughly 85,800 tonnes of meat wasted per year in that sector, equivalent to about 2% of national meat consumption; leftovers from overproduction and buffet or plate waste were identified as the largest waste-generating point in most business types, while weekly purchase volume and the number of distinct meat products offered were significant predictors of higher waste ratios [45]. The same survey estimated that halving food-service meat waste, in line with SDG Target 12.3, would avoid roughly 840,000 tonnes of CO_2-eq annually, comparable in scale to the processing-stage savings identified for Austria above, and identified smaller portion sizes and closer partnerships with food-redistribution organizations as concrete, low-cost prevention measures [45].

Circular economy, by-product valorization and the policy framework

Where loss cannot be entirely prevented, the circular-economy paradigm reframes unavoidable meat by-products and surplus as resources to be recovered rather than waste to be discarded, consistent with the EU's food-waste hierarchy, which prioritizes prevention, then redistribution/reuse, then recycling and recovery, over disposal [1, 46]. The EU Waste Framework Directive (2008/98/EC, revised as 2018/851/EC) operationalizes this hierarchy and, in line with UN Sustainable Development Goal Target 12.3, requires member states to halve per-capita food waste

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at the retail and consumer level and reduce losses along production and supply chains by 2030 [47, 48]. Comparable regional coordination exists elsewhere: an FAO regional initiative for Latin America and the Caribbean, built around a shared food-security action plan, documented national food-waste studies finding average waste rates above one-third across staple commodity baskets that included milk and meat products, illustrating that the measurement and policy challenges discussed here are not specific to Europe [49].

At the level of the carcass itself, the scale of the recoverable fraction is substantial: slaughter by-products can represent roughly two-thirds of live weight in cattle and lamb and around half in pigs, and a systematic review of animal-origin FLW catalogs an expanding set of upcycling routes for this material, including recovery of enzymes, collagen and blood-derived bioactive proteins, conversion into bioplastics, and biogas generation through anaerobic digestion of slaughterhouse blood and other residues [17]. Direct evidence of circular-economy application to meat by-products is provided by a study from our university converting cattle slaughterhouse by-products into bone broth: Anchidin et al. [50] note that only about one-third of a slaughtered animal becomes retail meat, with the remaining two-thirds consisting of by-products that would otherwise require costly disposal, and demonstrate that broths derived from juvenile and adult cattle bones differ significantly in protein (up to 22.1%) and collagen content (up to 20.4%), yielding a nutritionally valuable, microbiologically safe product from material that would otherwise be waste. This provides a direct illustration of the "waste-to-value" logic that Vilariño et al. [1], Lemaire and Limbourg [48] and Gonçalves et al. [17] describe more abstractly at EU and global scale, and it reinforces the case that circular-economy strategies for meat are most effective when designed around the specific by-product streams generated at the primary-processing stage, rather than only at the retail or household stages emphasized by most consumer-behavior literature. At system level, Xue et al. [47] show for the German meat chain that rendering of by-products and waste treatment adds up to a net greenhouse-gas benefit of about 5% of total chain emissions, comparable to the benefit of cutting retail and consumption meat waste by 25%, while a combination of waste reduction, process optimization, trade and dietary changes could lower total emissions by 43%.

At the policy level, Vilariño et al. [1] and Spang et al. [11] both caution that a persistent lack of harmonized, reliable FLW measurement, compounded by inconsistent definitions (as discussed above), undermines the ability of policy-makers to evaluate which interventions are actually effective, a gap that the FAO's Food Loss and Waste Protocol and the EU's own reporting obligations are only partially closing, as illustrated by the incomplete 2023 national data noted earlier [9, 11].

National evidence from Romania

National data allow the global patterns described above to be checked against a specific country. Trască et al. [51], using FAOSTAT data, document that Romanian meat consumption increased about 2.4-fold between 1961 and 2021, from 77 to 182 g/day/person (Fig. 8), a trajectory consistent with rising incomes and changing dietary patterns that, in the authors' assessment, now exceeds the levels considered optimal from a health or environmental perspective [51].

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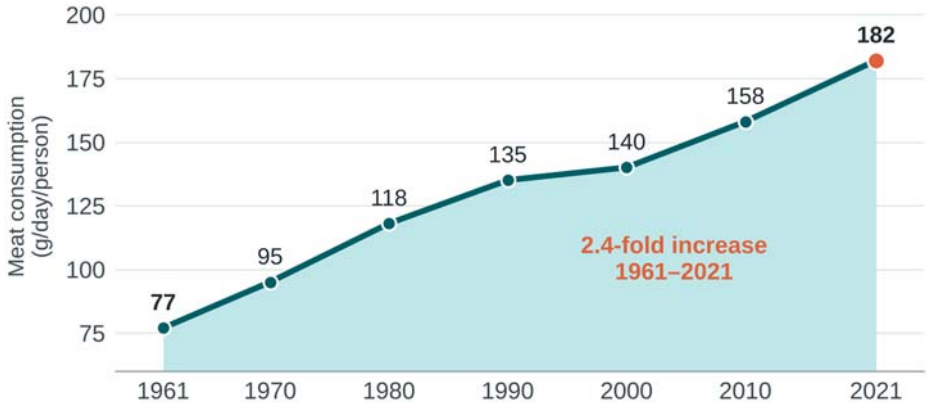


Fig. 8 Trend in meat consumption in Romania, 1961–2021 (g/day/person). Data: FAOSTAT, as compiled by Trască et al. [51].

Comparable evidence from Ukraine, where FAO-consistent stage-wise loss accounting attributed up to 72% of the national meat-consumption deficit to food loss and waste [24], indicates that the interaction between FLW and meat supply is not confined to a single country.

At the same time, domestic production does not keep pace with consumption: according to Ministry of Agriculture data cited by Trască et al. [51], approximately 70% of the beef and 60% of the pork consumed are imported, whereas the poultry self-sufficiency ratio is around 150% and roughly half of domestic chicken meat is exported. This asymmetric trade pattern implies that a meaningful share of the meat supply chain, and therefore of the associated cold-chain and food-waste exposure, occurs beyond national borders, which complicates any purely domestic policy response [51]. Cattle herds fell from over five million head in 1990 to fewer than one million at the time of the cited study, and, using a land-use-footprint model, the authors show that reducing weekly per-capita meat consumption by 100 g, preferably of ruminant meat, would meaningfully reduce the land footprint of national meat consumption, since beef requires roughly 20 times more land per 100 g than chicken [51].

Research on refrigerated-meat preservation and waste in Romania is more recent. Our recent review [7] synthesizes active and intelligent packaging technologies for refrigerated meat and frames packaging innovation as a food-waste-reduction strategy; a by-product valorization study [50] illustrates the waste-to-value logic discussed above; and a consumer survey in north-eastern Romania found that 70% of respondents would support the market introduction of cultured meat provided that food-safety and regulatory assurances were in place [52], a finding the authors relate to the national protein-supply deficit. Together, these studies show that the main strands of the international evidence, namely preservation technology, by-product valorization and alternative-protein acceptance, are all being addressed in national research, although an economic evaluation of preservation measures along the national meat chain was not found among the sources reviewed.

Emerging digital and systemic solutions

Across both the international and Romanian literature reviewed, digital technologies recur as a cross-cutting enabler rather than a standalone solution. Blockchain-based traceability, IoT-enabled cold-chain sensors, and AI-driven demand

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forecasting and dynamic pricing are each reported to reduce meat loss, IoT sensors by preventing undetected cold-chain excursions, AI-based pricing by clearing near-expiry inventory before it is discarded (with retail waste reductions of up to 30% reported), and blockchain by improving recall efficiency and reducing the counterfeiting/mislabeling risks that can otherwise force precautionary product withdrawal [6, 21]. A broader review of sustainable food-systems interventions reports comparable results elsewhere, for example post-harvest loss reductions of up to 30% from digitally enabled market platforms in East Africa, reinforcing that these digital gains are not confined to high-income cold-chain contexts [2]. Liorančas and Lee [53] extend this theme to the household level, showing that mobile applications designed to help consumers plan meals, track expiry dates and redistribute surplus food can measurably shift waste-related behavior, suggesting that digital tools are relevant not only to industrial supply-chain actors but also to closing the consumer-information gap identified in the date-labeling literature discussed above [29, 31].

Beyond meat-specific interventions, broader food-system research on surplus-food prevention offers transferable lessons for the refrigerated-meat sector. A Swedish doctoral evaluation of retail surplus-food redistribution and school-catering plate-waste tracking found that about 78% of redistributed retail surplus food was ultimately consumed and that donation outperformed anaerobic digestion in environmental-impact terms despite some rebound effects, while a plate-waste-tracking intervention combined with more popular menu choices achieved a sustained 17–19% reduction in school-meal waste [54]. Although developed for retail and catering more broadly rather than for meat specifically, this redistribution-and-monitoring model is directly transferable to near-expiry refrigerated meat, for which redistribution to food banks is already discussed as a concrete option in the food-service literature reviewed above [27, 45].

CONCLUSIONS

Meat loss and waste cannot be resolved by a single intervention. Meat and animal products show a global loss rate of 14.0% between post-harvest and retail, unchanged since 2015, and carry a disproportionate share of the greenhouse-gas and land-use footprint of food loss and waste. Where the losses arise differs by region: consumption dominates in the EU, whereas production and storage losses prevail where cold-chain infrastructure is weak. Preservation measures should therefore be stage-specific. Cold-chain investment pays most where refrigeration is least developed, whereas in industrialized markets packaging innovation, digital monitoring, standardized date labeling and consumer information offer the larger remaining margin.

The technical and economic evidence points in the same direction: packaging and cold-chain measures reduce waste only when their cost is lower than the waste they prevent, so they should be selected against the value density, shelf-life sensitivity and distribution length of each product, while cold-chain efficiency measures are the lower-risk option over a long horizon. For the unavoidable fraction, mainly by-products that represent about half to two-thirds of live weight, circular-economy valorization provides a complementary route. Priorities for future research are the industrial-scale economic evaluation of advanced packaging along real meat chains, harmonized measurement of meat loss and waste, and complete national baseline data. The originality of this review lies in linking the technical performance of preservation, cold-chain and circular-economy strategies to their economic viability within a single, stage-by-stage synthesis, which supports a

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cost-aware, combined approach to reducing food waste in the refrigerated meat sector.

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