THE ROLE OF PACKAGING IN BEEF QUALITY PRESERVATION: IMPLICATIONS FOR FOOD LOSS AND WASTE REDUCTION

A.-I. Nicodim*, R.-A. Drideanu, T. Ș. Vlad, M.-M. Lăpădat, R. A. Popa

University of Agronomic Sciences and Veterinary Medicine, Bucharest, Romania

Abstract

Packaging helps preserve chilled beef by controlling the gas environment around the meat. This review examines evidence on vacuum, vacuum skin and high-oxygen modified-atmosphere packaging to assess quality preservation and potential food-waste reduction. Vacuum-based systems can limit lipid oxidation, while vacuum skin packaging can reduce purge loss relative to conventional vacuum packaging. High-oxygen atmospheres can maintain redness but may impair tenderness and juiciness. Effects vary with ultimate pH and storage temperature. Higher pH can accelerate microbial growth, and high-pH beef may remain red under high-oxygen atmospheres despite spoilage. Packaging selection should therefore combine microbial, physicochemical and sensory criteria rather than rely on appearance alone. Environmental benefits depend on whether the impacts avoided through reduced beef waste outweigh those associated with packaging.

Key words: *beef, packaging, shelf life, microbial spoilage, food waste*

INTRODUCTION

Packaging helps determine the conditions under which chilled beef reaches consumers. By regulating oxygen exposure and limiting external contamination after sealing, it influences surface colour, oxidative deterioration and the development of spoilage microbiota. Vacuum packaging (VP), vacuum skin packaging (VSP) and modified-atmosphere packaging (MAP) offer different combinations of preservation and presentation. Advances in meat packaging have expanded these options, but their effectiveness depends on matching the atmosphere and barrier materials to the intended distribution conditions [1, 2]. Holman et al. therefore recommend defining preservation and commercial objectives before selecting a packaging system [3].

Colour is an important purchasing cue, but it provides an incomplete indication of beef preservation. Myoglobin chemistry responds to oxygen availability and muscle biochemistry, with oxygen consumption and metmyoglobin reduction contributing to differences in colour stability between muscles and products [4, 5]. Assessing the contribution of packaging to food loss reduction therefore requires consideration of microbial and eating quality alongside visual appearance.

Resource efficiency in livestock production depends on multiple factors, including reproductive performance, nutrition, animal welfare and management practices [6]. Beyond the production stage, maintaining meat quality during storage and distribution is equally important for minimizing product deterioration and potential food losses.

Although packaging technologies are widely studied for their effects on beef colour, oxidation, water losses and microbial spoilage, improvements in preservation do

*Corresponding author: iulianicodim@gmail.com

The manuscript was received: 18.10.2026
Accepted for publication: 19.11.2026

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

not necessarily demonstrate reductions in food discarded by retailers or consumers. A key challenge is to distinguish directly measured quality outcomes from hypothesised waste-prevention benefits and environmental effects. This distinction is important when comparing the additional material and storage burdens of packaging with the potential benefits of avoided beef losses [7, 8].

The environmental implications of preservation depend on the scope of the assessment. In a comparative life cycle assessment (LCA) of case-ready beef, the ranking of packaging systems changed when potential food waste was considered alongside packaging production and disposal [7]. This finding highlights the importance of including food losses in environmental comparisons, while recognising that an experimental extension of shelf life does not necessarily produce an equivalent reduction in commercial or household waste.

This review examines how VP, VSP and high-oxygen MAP influence chilled beef quality and considers the implications for food loss and waste reduction. It specifically addresses differences in physicochemical, sensory and microbial outcomes, the limits of interpreting shelf-life extension as avoided waste, and the evidence required for environmental comparison. Here, food loss refers to upstream supply-chain losses, while food waste refers to retail and household disposal. The synthesis considers colour, oxidation, purge, eating quality and microbial deterioration before discussing packaging selection and environmental assessment.

MATERIAL AND METHOD

This narrative review used targeted, non-systematic searches of scientific publisher and institutional websites, PubMed and Europe PMC to identify literature relevant to chilled beef packaging, quality preservation and potential food loss and waste reduction. Search terms included combinations of beef, vacuum packaging, vacuum skin packaging, modified-atmosphere packaging, meat quality, shelf life, food waste and life cycle assessment. The cited publications span 2003 to October 2026. The search was purposive rather than exhaustive; consequently, no comprehensive database record count or PRISMA-style screening flow is claimed.

Sources were selected for relevance to the review objectives. Comparative experiments on refrigerated beef packaged using VP, VSP or MAP were prioritised for conclusions about packaging performance. Reviews and measurement guidelines supplied mechanistic or methodological context, while LCA and food-waste papers informed the discussion of environmental implications. Studies involving other foods or broader livestock contexts were not treated as direct evidence of beef packaging performance. Selection was conducted without duplicate independent screening or a predefined risk-of-bias instrument.

The literature was organised thematically around colour stability, lipid and protein oxidation, water losses, tenderness, sensory characteristics and microbial deterioration. Results were compared in relation to meat characteristics, packaging conditions, ageing and storage procedures. The synthesis distinguished measured improvements in quality from potential reductions in food waste and associated environmental benefits.

Evidence was synthesised qualitatively because experimental designs, muscles, ageing and freezing sequences, film properties, storage temperatures and outcome definitions varied substantially. When interpreting comparisons, attention was given to the experimental comparator and to whether endpoints were measured during sealed storage or after opening. The review did not include a meta-analysis, and some sources were assessed only through abstracts or selected publisher content.

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

Numerical findings from these sources should therefore be treated as study-specific rather than pooled estimates.

RESULTS AND DISCUSSION

Packaging systems and oxygen exposure

VP and VSP both remove most of the air surrounding the meat, but differ in package construction and film contact with the product. Conventional vacuum bags may form folds in which exudate accumulates, whereas the upper film in VSP conforms closely to the meat and supporting surface. Stella et al. describe potential benefits of skin packaging for appearance, exudate management and preservation, while noting variation between studies [8]. VP and VSP should therefore be compared as distinct packaging formats within the broader group of vacuum-based systems.

High-oxygen MAP provides an oxygen-rich headspace, usually together with carbon dioxide. Many comparative beef studies reviewed here used 80% oxygen and 20% carbon dioxide. Findings from these mixtures apply to the tested atmospheres and should be distinguished from results obtained with low-oxygen MAP or carbon-monoxide atmospheres. Similarly, the designation VSP does not specify film permeability, residual oxygen, seal integrity or storage history. Meaningful comparisons require these characteristics to be reported alongside the packaging format [1, 8].

Colour development and stability

Across the reviewed studies, oxygen-rich packaging generally improved initial redness, while vacuum-based systems often provided greater colour stability during storage or subsequent exposure to air. These responses reflect changes in myoglobin state: oxygen binding produces red oxymyoglobin, oxygen depletion favours purplish deoxymyoglobin, and oxidation to metmyoglobin contributes to browning [4]. Lipid and myoglobin oxidation can reinforce one another, linking discolouration with flavour deterioration [9]. Initial redness and colour stability over time should therefore be assessed as separate outcomes.

Li et al. compared VP, VSP and high-oxygen MAP after seven days of vacuum ageing followed by seven days in the respective retail packages. Colour was then monitored during five days in air. VSP steaks had better colour stability than VP steaks, with colour similar to MAP at the end of aerobic storage [10]. This comparison concerns post-opening colour stability rather than unopened retail display.

Krell et al. examined six atmospheres at 2°C over 14 days using non-invasive measurements through the packaging. Vacuum treatments maintained relatively stable colour, while oxygen-containing treatments produced a more vivid red appearance. The experiment used previously frozen shoulder meat from three animals and storage without light [11]. These conditions limit extrapolation to fresh steaks displayed under retail lighting. Measuring colour through the package nevertheless allowed changes during sealed storage to be distinguished from those caused by opening.

Reyes et al. compared vacuum-ready film with polyvinyl chloride overwrap during a 35-day simulated display. Vacuum-packaged steaks showed more stable colour and lower oxidation, whereas overwrapped steaks were initially redder [12]. The results indicate improved preservation of these attributes, but a commercial shelf life of 35 days would also require microbial and sensory validation. Measurement procedures are another source of variation between studies. The American Meat Science Association guidelines specify reporting instrumental settings, including illuminant, aperture and observer, as well as whether measurements were taken through the packaging [13]. Consistent reporting helps distinguish product responses from methodological differences.

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

Oxidation and eating quality in high-oxygen packaging

The colour advantage of high oxygen must be weighed against oxidative and sensory changes. Kim et al. compared 80% oxygen/20% carbon dioxide MAP with vacuum packaging in three beef muscles during nine days of display at 1°C. High-oxygen steaks exhibited greater lipid oxidation, poorer tenderness and juiciness scores, and more off-flavour. Protein analyses identified oxidative cross-linking of myosin, while measured degradation of desmin and troponin-T and calpain autolysis were not altered by packaging [14]. Thus, the observed toughening cannot simply be attributed to inhibited postmortem proteolysis.

Lagerstedt et al. reported higher shear force and poorer sensory tenderness and juiciness with high-oxygen MAP than with VP; samples were frozen after the assigned ageing and packaging treatments and assessed subsequently [15]. Clausen et al. likewise reported greater warmed-over flavour and oxidation, together with poorer eating quality, in systems involving high oxygen. Their observation of a lower myofibrillar fragmentation index suggests that the relative contributions of proteolysis and oxidation vary with experimental conditions [16]. Taken together, these findings implicate oxidative damage in quality deterioration, while allowing for differences in the underlying mechanisms.

Consumer assessments indicate that these changes can affect overall eating quality. Geesink et al. reported an approximately eight-point reduction in the composite Meat Standards Australia MQ4 eating-quality score with high-oxygen MAP compared with skin packaging, without a change in desmin degradation [17]. Polkinghorne et al. reported decreases of approximately 10–12 points on 100-point sensory scales for high-oxygen MAP relative to overwrap or VSP across their muscle and ageing comparisons [18]. These effects should be interpreted within each study because differences in sensory scales and experimental designs preclude direct pooling.

The tenderness response also depends on product form and packaging sequence. Lindahl et al. found a similar decline in shear force when large loin cuts were aged directly in high oxygen or vacuum, in contrast to several steak experiments [19]. Moczkowska et al. reported muscle-dependent changes in protein degradation and oxidation; combining VSP and MAP maintained redness without improving tenderness [20]. These findings indicate that high oxygen does not produce the same tenderness response under all conditions.

Oxygen concentration and prior ageing further influence the balance between appearance and eating quality. Zakrys et al. compared five oxygen concentrations and found a sensory preference for the 50% treatment despite detectable oxidised flavours [21]. In mature-cow beef, Vitale et al. found that prolonged vacuum ageing before high-oxygen display reduced colour and lipid stability without improving tenderness beyond that achieved with shorter ageing periods [22]. Longer ageing can therefore reduce stability during subsequent retail display without providing an additional tenderness benefit. Overall, raw appearance and cooked acceptability should be assessed together; whether poorer eating quality leads to greater household waste remains to be established.

Purge and other quality responses to vacuum skin packaging

Several comparisons indicate that VSP can reduce purge relative to conventional VP, although the benefit does not consistently extend to total water loss, tenderness or sensory quality. This distinction matters because purge, cooking loss and other water-loss measurements describe different processes. Lagerstedt et al. found less purge with VSP than with conventional VP, but no detectable differences in total loss, shear force or sensory assessment [23]. Samples were frozen after the storage treatments, which should be considered when interpreting the

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

findings. Reduced purge alone therefore provides insufficient evidence of improved total yield or cooked juiciness.

Strydom and Hope-Jones compared VSP steaks, vacuum-packed steaks and primal VP followed by portioning/repacking over 21 days. Purge was 1.09% with VSP versus 3.45% and 3.40% in the other sequences. Tenderness did not differ significantly, while VSP improved subsequent aerobic colour stability [24].

Evidence for a consistent tenderness advantage of VSP is less clear. Clausen et al. found lower tenderness with one skin-packaging sequence than with a nitrogen-storage sequence [16]. Łopacka et al. reported effects of packaging method and storage duration on physicochemical traits, particularly colour and lipid oxidation [25]. These comparisons underline the importance of the comparator and processing sequence. Assessments of cooked appearance also require care: high-oxygen samples showed premature browning in comparative experiments, making cooked colour alone an unreliable indicator of doneness [16, 23].

Related studies of advanced skin packaging by Barros-Velázquez et al. and Vázquez et al. reported lower microbial counts but greater firmness or slower tenderisation than conventional VP [26, 27]. The reports are considered together because the independence of their samples could not be established from the accessible material. Variation also occurs within conventional VP. Stella et al. compared shrinkable barrier bags sealed in a vacuum-chamber machine with thermoformed packs of shank cuts. After 20 days at 2–3°C, mean drip loss was 1.04% and 1.71%, respectively, with relatively small effects on other measured attributes [28]. Exudate retention thus depends on package construction and processing conditions as well as the broad packaging category.

Microbial ecology and storage temperature

The effects of packaging on oxidation and water loss must be considered alongside its influence on microbial spoilage. Oxygen removal changes the conditions in which microorganisms develop, but does not eliminate them. Nychas et al. describe spoilage in relation to the activity of particular organisms under prevailing storage conditions [29]. Consistent with this framework, Mansur et al. found predominantly *Pseudomonas*-associated communities in air-stored beef and lactic acid bacteria in vacuum-stored beef, accompanied by different volatile and off-odour profiles [30]. Spoilage indicators may therefore differ between packaging atmospheres.

Across the primary studies, packaging atmosphere influenced microbial succession and spoilage-related metabolites, with outcomes also depending on storage temperature and the initial microbiota. Pennacchia et al. found that vacuum storage reduced viable counts of several spoilage groups without necessarily reducing species diversity [31]. Ercolini et al. compared air with two oxygen-containing modified atmospheres at 5°C and observed microbial succession that differed with the initial atmosphere [32]. Their experiment did not include VP, so it supports an atmosphere-dependent effect rather than a direct inference about oxygen removal. At 6°C, Jääskeläinen et al. found distinct community and volatile profiles in vacuum and high-oxygen beef; sensory spoilage occurred earlier in their high-oxygen treatment [33]. These comparisons support combining enumeration, community analysis and sensory endpoints rather than treating one total count as a complete description of deterioration.

Gas-producing spoilage remains possible under vacuum. Wambui and Stephan review the role of Clostridium estertheticum in blown-pack spoilage [34]. Low oxygen therefore changes spoilage risks rather than removing them, and the absence of package swelling provides only limited information about microbiological acceptability. Shelf-life validation should assess the relevant organisms under the intended temperature conditions, alongside

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

visual and sensory observations. Microbiological spoilage indicators should not be equated with food-safety validation: visual appearance, odour and total viable counts do not necessarily establish the absence of relevant pathogens.

The importance of temperature is illustrated by de Freitas et al., who stored vacuum-packed beef at 4°C or 15°C for 28 days and used culture-based methods and sequencing to assess microbial changes. Blown packs occurred in most samples at 15°C between days 14 and 28, but were not observed at 4°C. The warmer condition also altered microbial abundance and community composition [35]. These findings demonstrate the consequences of temperature abuse; acceptability throughout 28 days at 4°C would still require assessment of the other relevant quality and microbial endpoints.

Microbial behaviour under vacuum also warrants closer examination. Yang et al. investigated *Pseudomonas* growth and interactions with lactic acid bacteria in VSP beef [36]. This work supports assessing the community that develops under the actual film and storage conditions, rather than relying solely on an expected division between aerobic and anaerobic organisms.

Film barrier and antimicrobial effects should be distinguished. During 120 days of storage, Rovira et al. observed higher *Pseudomonas* and Enterobacteriaceae counts in chilled beef packed in a high-oxygen-permeability film containing an antimicrobial than in a low-permeability film without it. Because both film permeability and antimicrobial treatment differed, their separate contributions cannot be isolated. Refrigeration followed by freezing produced lower final microbial counts than continuous refrigeration, while no overt signs of deterioration were reported in any treatment [37]. A 2025 longitudinal study by Roch et al. extended the ecological analysis to fungi, documenting bacterial–yeast interactions during VP beef storage [38]. Such interactions help explain why community composition and spoilage potential cannot be inferred from oxygen concentration alone.

Ultimate pH and the relationship between appearance and spoilage

Meat characteristics can further modify packaging performance, particularly ultimate pH. Yang et al. classified beef as normal pH, 5.40–5.79; intermediate pH, 5.80–6.09; or high pH, at least 6.10, and evaluated VP and modified atmospheres during 14 days at 2°C. Higher-pH meat supported faster microbial proliferation despite lower purge and lipid oxidation. Under high-oxygen and carbon-monoxide MAP, high-pH steaks could remain bright red even after spoilage [39]. The pH categories were defined for that experiment and should be distinguished from commercial grading criteria.

These findings show why lower purge, reduced oxidation or persistent redness cannot individually establish product acceptability. Assessments should consider initial pH together with visual, sensory and microbial endpoints [39]. Carbon-monoxide MAP is included here as an experimental comparator.

Wu et al. found a muscle-dependent colour response, although high-pH longissimus lumborum and psoas major differed substantially in achieved pH (6.92 and 6.01), limiting attribution to muscle alone [40]. Lu et al. compared four normal-pH and four dark-cutting carcasses during 14 days in the dark at 2°C. Higher oxygen improved dark-cutting appearance, while 60% oxygen caused less lipid oxidation than 80% [41]. This illustrates the balance between colour improvement and oxidative stability in dark-cutting beef.

Table 1 summarises selected comparisons, retaining the experimental conditions needed to interpret their findings. Table 2 draws together the quality, storage and environmental considerations discussed throughout this review into questions for practical packaging validation.

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

Table 1 Selected comparisons of packaging and chilled beef quality

Study and comparison	Principal observation	Interpretation
Kim et al. [14] High-oxygen MAP versus VP; 9 days at 1°C	Higher lipid oxidation and poorer sensory traits with high oxygen; myosin cross-linking observed.	n = 10 reported per muscle; three muscles. Measured degradation was unchanged.
Geesink et al. [17] MAP versus skin packaging after vacuum ageing	High-oxygen MAP lowered the composite eating-quality score by about 8 points.	MQ4 score; sequential ageing and display. Biological n not verified here.
Strydom and Hope-Jones [24] Three vacuum sequences; 21 days of ageing	Purge was 1.09% in VSP versus 3.45% and 3.40% in the other treatments.	No significant tenderness effect. Portioning/repacking differed; biological n not verified.
de Freitas et al. [35] VP beef at 4°C or 15°C for 28 days	Blown packs were observed at 15°C, but not at 4°C, in this experiment.	Swelling alone cannot define shelf life or safety.
Yang et al. [39] Three pH classes; VP and MAP; 14 days at 2°C	High-pH beef supported faster microbial growth; redness could persist after spoilage under MAP.	The pH classes and atmospheres are study-specific. Colour cannot replace microbial assessment.
Lee et al. [42] VP/VSP with or without oxygen absorbers; 28-day wet ageing	Oxygen absorbers improved colour stability; VSP retarded lipid oxidation.	Chikso *semimembranosus*; incremental benefits need confirmation in other products.
Yu et al. [43] Air, VP and VSP during 35-day wet ageing	VSP performed better for microbial stability, oxidation and tenderness; a 35-day shelf life was reported.	Abstract-based result; duration and rejection criteria need full-text appraisal.

Note: *1. VP: vacuum packaging; VSP: vacuum skin packaging; MAP: modified-atmosphere packaging; MQ4: composite Meat Standards Australia eating-quality score; n: reported sample size*

Table 2 Questions for validating packaging selection

Decision context	Quality question	Evidence needed before implementation
Visible redness is a sales priority	Does attractive colour coexist with acceptable eating quality?	Assess raw colour, oxidation and cooked sensory quality together [14, 18].
Purge limits presentation or yield	Does less exudate improve yield or acceptability?	Separate purge, total loss and sensory response [23, 24].
High-pH or variable raw material	Can spoilage precede visible rejection?	Stratify by pH; assess microbial, sensory and colour endpoints [39].
Temperature excursions are possible	Does validation cover the actual cold chain?	Record temperatures and validate relevant deviations [35].
A sustainability benefit is claimed	What beef losses and extra burdens are avoided or created?	Measure disposal; test waste, packaging and refrigeration assumptions [7, 44].

Note: *VSP, vacuum skin packaging; pH, measure of acidity or alkalinity.*

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

Complementary approaches to preservation and monitoring

Beyond the packaging format itself, active and intelligent technologies can address specific preservation and monitoring needs. Active components modify conditions affecting the product, while intelligent systems monitor the food or its environment [45]. The benefit of monitoring depends on whether the information supports an effective handling or storage decision.

Oxygen absorbers offer one means of refining oxygen control within vacuum-based systems. Lee et al. compared conventional VP and VSP, with and without absorbers, during 28 days of wet ageing of Chikso semimembranosus. Absorbers improved colour stability, VSP retarded lipid oxidation, and their combination reduced visually assessed discolouration [42]. The findings support control of residual oxygen as a complementary strategy, with performance dependent on the product and storage conditions.

The preservation achieved by VSP alone also continues to be investigated. Yu et al. compared air, VP and VSP during 35 days of wet ageing of longissimus lumborum. VSP provided better microbiological stability, tenderness and oxidative control in that experiment, and the authors reported a 35-day shelf life for the VSP treatment [43]. Differences from earlier studies may reflect packaging materials, procedures or biological variation, but the accessible evidence does not allow these contributions to be separated. The reported shelf life should therefore be interpreted within the tested system.

Other interventions target microbial growth or temperature control. Yu et al. combined VSP with grapefruit seed extract, cinnamaldehyde and nisin and reported improved oxidative and microbial outcomes relative to the tested comparators [46]. Singh et al. developed expanded-polypropylene transport boxes with a thermoregulating coating and reported temperature control and acceptable beef-quality indicators during three hours of ambient exposure [47]. The short exposure period limits conclusions about protection during prolonged temperature abuse. As these interventions address different preservation needs, each requires validation before their combined use can be evaluated.

To identify the contribution of each intervention, future comparisons should distinguish changes in packaging format from simultaneous changes in film permeability, active components or handling, and report meat characteristics and temperature history.

From shelf-life extension to avoided food waste

The preceding studies primarily demonstrate changes in quality and spoilage. Their implications for waste reduction require a further step: measuring whether improved preservation actually reduces the amount of beef discarded. Environmental assessment must then weigh the benefits of avoided losses against the additional impacts of packaging and storage. Evidence for quality preservation is currently more direct than evidence for reduced beef disposal.

Casson et al. compared overwrap, high-oxygen MAP and vacuum skin systems using a 500-g sliced-beef package as the functional unit. Overwrap performed favourably when only packaging was assessed, whereas vacuum skin performed best when modelled potential food waste was included. Waste estimates were derived from a relationship between relative shelf life and potential waste, rather than direct observations of household beef disposal [7]. The study illustrates how accounting for preservation can change LCA results, with the outcome dependent on the waste assumptions used.

Zhang et al. evaluated active packaging for fresh beef using comparative LCA and sensitivity analysis. Their scenarios

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

examined whether reductions in food loss could offset additional packaging impacts and identified break-even conditions for the environmental categories assessed [44]. Although the active treatment differs from the main packaging formats considered here, the approach provides a useful basis for evaluating the loss reduction needed to offset an intervention's additional impacts.

For a proposed change in packaging, an environmental benefit is achieved when the additional impact of packaging and storage is lower than the impact avoided through reduced beef loss.

This relationship provides a conceptual criterion; no such calculation was performed in the present review. Environmental impacts must be compared within the same impact category, functional unit and system boundary, because a packaging option may perform differently across impact categories. Expressing results per kilogram of beef consumed and testing assumptions about waste rates, storage duration and disposal can reveal effects overlooked when packaging is assessed in isolation [7, 44, 48].

Consumer use can also determine whether a longer unopened shelf life prevents waste. Unsuitable portion sizes or handling difficulties may limit the benefit, while the possibility that unfamiliar low-oxygen colour prompts rejection requires direct investigation. Wohner et al. identify packaging size, usability and other design attributes as potential drivers of food loss and waste [49]. Williams et al. examined packaging-related reasons for disposal through household food-waste diaries, and Verghese et al. considered opportunities across the supply chain [50, 51]. These cross-food studies support attention to consumer use and handling, but do not quantify beef waste prevented by VP or VSP. Retail and household measurements are needed to determine whether preservation reduces disposal, shifts it between stages or delays rejection.

Integrating the evidence into packaging selection

Together, these findings support selecting packaging against a defined combination of quality, storage and environmental objectives. In practice, a proposed shelf life must be supported by the earliest relevant rejection endpoint among microbial spoilage, oxidation, sensory acceptability and appearance under the intended conditions; food-safety validation is a separate requirement. Table 2 outlines corresponding practical questions. High oxygen is associated with poorer eating quality in several steak comparisons, whereas VSP reduces purge in selected systems; tenderness advantages and reported shelf-life durations are less consistent.

The initial condition of the meat is central to this assessment. Feng et al. compared 30%, 50% and 70% oxygen at two initial microbial-load levels over 20 days. Oxygen concentration affected colour and oxidative responses differently between load classes, without changing bacterial counts or diversity in that experiment [52]. These results indicate that initial contamination can modify quality responses to oxygen concentration and should be considered when evaluating alternative atmospheres.

Material selection adds a further environmental consideration. Mukta et al. combined material performance testing with cradle-to-gate LCA of ground-beef packaging; selected alternative films showed lower modelled impacts and favourable colour retention [53]. Establishing an advantage through to consumption would additionally require consideration of storage, disposal and actual food waste. Future studies should therefore pair packaging-performance measurements with the mass and causes of discarded beef, using a common functional unit for environmental comparisons.

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

Limitations of the evidence

Interpretation of the evidence is constrained by differences in biological sample size, ageing, freezing and display sequence. For example, the many steaks assessed by Reyes et al. originated from seven animals, so the number of steaks should be distinguished from the number of independent biological samples [12]. Related reports were also treated cautiously where overlap between samples could not be resolved.

Observational findings introduce further uncertainty about causation. Poveda et al. compared 12 discoloured and 12 control vacuum-packed samples, but microbial counts and identification did not fully explain the colour difference [54]. Such a comparison cannot isolate packaging effects from animal history or initial microbiota. At review level, the targeted search, incomplete access to full texts and absence of formal risk-of-bias assessment limit the completeness and certainty of the synthesis. In particular, evidence of measured beef-waste reduction remains less direct than evidence of changes in quality.

CONCLUSIONS

Vacuum-based packaging generally supports oxidative stability, while VSP can reduce purge relative to conventional VP in some experimental systems. High-oxygen MAP promotes initial redness but may adversely affect cooked eating quality. These trade-offs depend on meat characteristics, packaging materials, ageing and actual storage conditions.

For practical packaging selection, colour should not be used as a stand-alone proxy for freshness or acceptability. Validation should combine ultimate pH, initial contamination and temperature history with physicochemical, spoilage-related microbial and sensory endpoints. Food-safety requirements must be assessed independently of visual and spoilage indicators.

Shelf-life extension alone does not establish that less beef is discarded. A defensible environmental comparison therefore requires observed or transparently modelled losses alongside packaging and storage impacts, using consistent functional units, system boundaries and impact categories. The practical contribution of this review is to identify the evidence needed to move from measured preservation to credible waste-prevention and environmental claims.

REFERENCES

1. McMillin, KW Advancements in meat packaging. *Meat Sci.* **2017**, *132*, 153–162. https://doi.org/10.1016/j.meatsci.2017.04.015
2. McMillin, KW Where is MAP Going? A review and future potential of modified atmosphere packaging for meat. *Meat Sci.* **2008**, *80*, 43–65. https://doi.org/10.1016/j.meatsci.2008.05.028
3. Holman, BWB; Kerry, JP; Hopkins, DL Meat packaging solutions to current industry challenges: A review. *Meat Sci.* **2018**, *144*, 159–168. https://doi.org/10.1016/j.meatsci.2018.04.026
4. Suman, SP; Joseph, P. Myoglobin Chemistry and Meat Color. *Annu. Rev. Food Sci. Technol.* **2013**, *4*, 79–99. https://doi.org/10.1146/annurev-food-030212-182623
5. Mancini, RA; Hunt, MC Current research in meat color. *Meat Sci.* **2005**, *71*, 100–121. https://doi.org/10.1016/j.meatsci.2005.03.003
6. Luca, M.; Moise, AE; Drideanu, R-A; Gheciu Pîrlea, GM; Răducuță, I. Reproductive Performance in Sheep under Organic and Conventional Farming Systems. Scientific Papers: *Animal Science and Biotechnologies* **2026**, 59(1), 92–103. https://www.spasb.ro/index.php/public_html/article/view/2463
7. Casson, A.; Giovenzana, V.; Frigerio, V.; Zambelli, M.; Beghi, R.; Pampuri, A.; Tugnolo, A.; Merlini, A.; Colombo, L.; Limbo, S.; Guidetti, R. Beyond the eco-design of case-ready beef packaging: The relationship between food waste and shelf-life as a key element in life cycle assessment. *Food Packag. Shelf Life* **2022**, *34*, 100943. https://doi.org/10.1016/j.fpsl.2022.100943

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

8. Stella, S.; Bernardi, C.; Tirloni, E. Influence of Skin Packaging on Raw Beef Quality: A Review. *J. Food Qual.* **2018**, *2018*, 7464578. https://doi.org/10.1155/2018/7464578
9. Faustman, C.; Sun, Q.; Mancini, R.; Suman, SP Myoglobin and lipid oxidation interactions: Mechanistic bases and control. *Meat Sci.* **2010**, *86*, 86–94. https://doi.org/10.1016/j.meatsci.2010.04.025
10. Li, X.; Lindahl, G.; Zamaratskaia, G.; Lundström, K. Influence of vacuum skin packaging on color stability of beef longissimus lumborum compared with vacuum and high-oxygen modified atmosphere packaging. *Meat Sci.* **2012**, *92*, 604–609. https://doi.org/10.1016/j.meatsci.2012.06.006
11. Krell, J.; Poveda-Arteaga, A.; Weiss, J.; Witte, F.; Terjung, N.; Gibis, M. Influence of different storage atmospheres in packaging on color stability of beef. *J. Food Sci.* **2024**, *89*, 5774–5787. https://doi.org/10.1111/1750-3841.17286
12. Reyes, TM; Wagoner, MP; Zorn, VE; Coursen, MM; Wilborn, BS; Bonner, T.; Brandebourg, TD; Rodning, SP; Sawyer, JT Vacuum Packaging Can Extend Fresh Color Characteristics of Beef Steaks during Simulated Display Conditions. *Foods* **2022**, *11*, 520. https://doi.org/10.3390/foods11040520
13. King, DA; Hunt, MC; Barbut, S.; Claus, JR; Cornforth, DP; Joseph, P.; Kim, YHB; Lindahl, G.; Mancini, RA; Nair, MN; Merok, KJ; Milkowski, A.; Mohan, A.; Pohlman, F.; Ramanathan, R.; Raines, CR; Seyfert, M.; Sørheim, O.; Suman, SP; Weber, M. American Meat Science Association Guidelines for Meat Color Measurement. *Meat Muscle Biol.* **2023**, *6*, 12473, 1–81. https://doi.org/10.22175/mmb.12473
14. Kim, YH; Huff-Lonergan, E.; Sebranek, JG; Lonergan, SM High-oxygen modified atmosphere packaging system induces lipid and myoglobin oxidation and protein polymerization. *Meat Sci.* **2010**, *85*, 759–767. https://doi.org/10.1016/j.meatsci.2010.04.001
15. Lagerstedt, Å.; Lundström, K.; Lindahl, G. Influence of vacuum or high-oxygen modified atmosphere packaging on quality of beef M. longissimus dorsi steaks after different ageing times. *Meat Sci.* **2011**, *87*, 101–106. https://doi.org/10.1016/j.meatsci.2010.08.010
16. Clausen, I.; Jakobsen, M.; Ertbjerg, P.; Madsen, NT Modified atmosphere packaging affects lipid oxidation, myofibrillar fragmentation index and eating quality of beef. *Packag. Technol. Sci.* **2009**, *22*, 85–96. https://doi.org/10.1002/pts.828
17. Geesink, G.; Robertson, J.; Ball, A. The effect of retail packaging method on objective and consumer assessment of beef quality traits. *Meat Sci.* **2015**, *104*, 85–89. https://doi.org/10.1016/j.meatsci.2015.02.006
18. Polkinghorne, RJ; Philpott, J.; Perovic, J.; Lau, J.; Davies, L.; Mudannayake, W.; Watson, R.; Tarr, G.; Thompson, JM The effect of packaging on consumer eating quality of beef. *Meat Sci.* **2018**, *142*, 59–64. https://doi.org/10.1016/j.meatsci.2018.04.002
19. Lindahl, G.; Lagerstedt, Å.; Ertbjerg, P.; Sampels, S.; Lundström, K. Ageing of large cuts of beef loin in vacuum or high oxygen modified atmosphere – Effect on shear force, calpain activity, desmin degradation and protein oxidation. *Meat Sci.* **2010**, *85*, 160–166. https://doi.org/10.1016/j.meatsci.2009.12.020
20. Moczkowska, M.; Półtorak, A.; Montowska, M.; Pospiech, E.; Wierzbicka, A. The effect of the packaging system and storage time on myofibrillar protein degradation and oxidation process in relation to beef tenderness. *Meat Sci.* **2017**, *130*, 7–15. https://doi.org/10.1016/j.meatsci.2017.03.008
21. Zakrys, PI; Hogan, SA; O'Sullivan, MG; Allen, P.; Kerry, JP Effects of oxygen concentration on the sensory evaluation and quality indicators of beef muscle packed under modified atmosphere. *Meat Sci.* **2008**, *79*, 648–655. https://doi.org/10.1016/j.meatsci.2007.10.030
22. Vitale, M.; Pérez-Juan, M.; Lloret, E.; Arnau, J.; Realini, CE Effect of aging time in vacuum on tenderness, and color and lipid stability of beef from mature cows during display in high oxygen atmosphere package. *Meat Sci.* **2014**, *96*, 270–277. https://doi.org/10.1016/j.meatsci.2013.07.027
23. Lagerstedt, Å.; Ahnström, ML; Lundström, K. Vacuum skin pack of beef - A consumer friendly alternative. *Meat Sci.* **2011**, *88*, 391–396. https://doi.org/10.1016/j.meatsci.2011.01.015
24. Strydom, PE; Hope-Jones, M. Evaluation of three vacuum packaging methods for retail beef loin cuts. *Meat Sci.* **2014**, *98*, 689–694. https://doi.org/10.1016/j.meatsci.2014.05.030
25. Łopacka, J.; Półtorak, A.; Wierzbicka, A. Effect of MAP, vacuum skin-pack and combined packaging methods on physicochemical properties of beef steaks stored up to 12 days. *Meat Sci.* **2016**, *119*, 147–153. https://doi.org/10.1016/j.meatsci.2016.04.034

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

26. Barros-Velázquez, J.; Carreira, L.; Franco, C.; Vázquez, BI; Fente, C.; Cepeda, A. Microbiological and Physicochemical Properties of Fresh Retail Cuts of Beef Packaged under an Advanced Vacuum Skin System and Stored at 4 °C. *J. Food Prot.* **2003**, *66*, 2085–2092. https://doi.org/10.4315/0362-028X-66.11.2085
27. Vázquez, BI; Carreira, L.; Franco, C.; Fente, C.; Cepeda, A.; Barros-Velázquez, J. Shelf life extension of beef retail cuts subjected to an advanced vacuum skin packaging system. *Eur. Food Res. Technol.* **2004**, *218*, 118–122. https://doi.org/10.1007/s00217-003-0837-6
28. Stella, S.; Garavaglia, D.; Francini, G.; Viganò, V.; Bernardi, C.; Tirloni, E. Evaluation of the weight loss of raw beef cuts vacuumpackaged with two different techniques. *Ital. J. Food Saf.* **2019**, *8*, 8111. https://doi.org/10.4081/ijfs.2019.8111
29. Nychas, GJE; Skandamis, PN; Tassou, CC; Koutsoumanis, KP Meat spoilage during distribution. *Meat Sci.* **2008**, *78*, 77–89. https://doi.org/10.1016/j.meatsci.2007.06.020
30. Mansur, AR; Song, EJ; Cho, YS; Nam, YD; Choi, YS; Kim, DO; Seo, DH; Nam, TG Comparative evaluation of spoilage-related bacterial diversity and metabolite profiles in chilled beef stored under air and vacuum packaging. *Food Microbiol.* **2019**, *77*, 166–172. https://doi.org/10.1016/j.fm.2018.09.006
31. Pennacchia, C.; Ercolini, D.; Villani, F. Spoilage-related microbiota associated with chilled beef stored in air or vacuum pack. *Food Microbiol.* **2011**, *28*, 84–93. https://doi.org/10.1016/j.fm.2010.08.010
32. Ercolini, D.; Russo, F.; Torrieri, E.; Masi, P.; Villani, F. Changes in the Spoilage-Related Microbiota of Beef during Refrigerated Storage under Different Packaging Conditions. *Appl. Environ. Microbiol.* **2006**, *72*, 4663–4671. https://doi.org/10.1128/AEM.00468-06
33. Jääskeläinen, E.; Hultman, J.; Parshintsev, J.; Riekkola, ML; Björkroth, J. Development of spoilage bacterial community and volatile compounds in chilled beef under vacuum or high oxygen atmospheres. *Int. J. Food Microbiol.* **2016**, *223*, 25–32. https://doi.org/10.1016/j.ijfoodmicro.2016.01.022
34. Wambui, J.; Stephan, R. Relevant Aspects of Clostridium estertheticum as a Specific Spoilage Organism of Vacuum-Packed Meat. *Microorganisms* **2019**, *7*, 142. https://doi.org/10.3390/microorganisms7050142
35. de Freitas, CF; Carvalho, LMVF; Camargo, AC; de Almeida, OGG; de Oliveira, RR; De Martinis, EP; Yamatogi, RS; Nero, LA Bacterial microbiota shifts in vacuum-packed beef during storage at different temperatures: Impacts on blown pack spoilage. *Food Microbiol.* **2024**, *119*, 104448. https://doi.org/10.1016/j.fm.2023.104448
36. Yang, J.; Rong, G.; Liang, R.; Zhu, L.; Mao, Y.; Luo, X.; Zhang, Y.; Yang, X. New insights into the growth characteristics, bacterial interaction and spoilage contribution of Pseudomonas species in vacuum skin packaged beef. *Food Packag. Shelf Life* **2025**, *52*, 101622. https://doi.org/10.1016/j.fpsl.2025.101622
37. Rovira, P.; Brugnini, G.; Rodriguez, J.; Cabrera, MC; Saadoun, A.; de Souza, G.; Luzardo, S.; Rufo, C. Microbiological Changes during Long-Storage of Beef Meat under Different Temperature and Vacuum-Packaging Conditions. *Foods* **2023**, *12*, 694. https://doi.org/10.3390/foods12040694
38. Roch, FF; Dzieciol, M.; Strachan, CR; Chaughtai, MS; Quijada, NM; Movsesijan, T.; Selberherr, E. Microbial succession and interaction in vacuum-packed beef: a longitudinal study of bacterial and fungal dynamics. *npj Sci. Food* **2025**, *9*, 105. https://doi.org/10.1038/s41538-025-00479-8
39. Yang, X.; Wang, J.; Holman, BWB; Liang, R.; Chen, X.; Luo, X.; Zhu, L.; Hopkins, DL; Zhang, Y. Investigation of the physicochemical, bacteriological, and sensory quality of beef steaks held under modified atmosphere packaging and representative of different ultimate pH values. *Meat Sci.* **2021**, *174*, 108416. https://doi.org/10.1016/j.meatsci.2020.108416
40. Wu, S.; Han, J.; Liang, R.; Dong, P.; Zhu, L.; Hopkins, DL; Zhang, Y.; Luo, X. Investigation of muscle-specific beef color stability at different ultimate pHs. *Asian-Australas. J. Anim. Sci.* **2020**, *33*, 1999–2007. https://doi.org/10.5713/ajas.19.0943
41. Lu, X.; Cornforth, DP; Carpenter, CE; Zhu, L.; Luo, X. Effect of oxygen concentration in modified atmosphere packaging on color changes of the M. longissimus thoraces et lumborum from dark cutting beef carcasses. *Meat Sci.* **2020**, *161*, 107999. https://doi.org/10.1016/j.meatsci.2019.107999
42. Lee, D.; Kim, HJ; Lee, S.; Choi, M.; Kumar, SA; Jo, C. The combined effect of vacuum-

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)

skin packaging and oxygen absorbers on the color stability and physicochemical properties of wet-aged Chikso beef. *Food Packag. Shelf Life* **2024**, *43*, 101275. https://doi.org/10.1016/j.fpsl.2024.101275
43. Yu, H.; Yan, J.; Zou, B.; Zhang, S.; Xie, P.; Liu, X.; Lei, Y.; Sun, B.; Zang, M. Vacuum skin packaging versus traditional methods: A decisive advantage in controlling oxidation and volatile flavor profiles of wet-aged beef. *Food Chem.* **2026**, *510*, 148722. https://doi.org/10.1016/j.foodchem.2026.148722
44. Zhang, H.; Hortal, M.; Dobon, A.; Bermudez, JM; Lara-Lledo, M. The Effect of Active Packaging on Minimizing Food Losses: Life Cycle Assessment (LCA) of Essential Oil Component-enabled Packaging for Fresh Beef. *Packag. Technol. Sci.* **2015**, *28*, 761–774. https://doi.org/10.1002/pts.2135
45. Realini, CE; Marcos, B. Active and intelligent packaging systems for a modern society. *Meat Sci.* **2014**, *98*, 404–419. https://doi.org/10.1016/j.meatsci.2014.06.031
46. Yu, HH; Kim, YJ; Park, YJ; Shin, DM; Choi, YS; Lee, NK; Paik, HD Application of mixed natural preservatives to improve the quality of vacuum skin packaged beef during refrigerated storage. *Meat Sci.* **2020**, *169*, 108219. https://doi.org/10.1016/j.meatsci.2020.108219
47. Singh, S.; Gaikwad, KK; Lee, M.; Lee, YS Temperature sensitive smart packaging for monitoring the shelf life of fresh beef. *J. Food Eng.* **2018**, *234*, 41–49. https://doi.org/10.1016/j.jfoodeng.2018.04.014
48. Williams, H.; Wikström, F. Environmental impact of packaging and food losses in a life cycle perspective: a comparative analysis of five food items. *J. Clean. Prod.* **2011**, *19*, 43–48. https://doi.org/10.1016/j.jclepro.2010.08.008
49. Wohner, B.; Pauer, E.; Heinrich, V.; Tacker, M. Packaging-Related Food Losses and Waste: An Overview of Drivers and Issues. *Sustainability* **2019**, *11*, 264. https://doi.org/10.3390/su11010264
50. Williams, H.; Wikström, F.; Otterbring, T.; Löfgren, M.; Gustafsson, A. Reasons for household food waste with special attention to packaging. *J. Clean. Prod.* **2012**, *24*, 141–148. https://doi.org/10.1016/j.jclepro.2011.11.044
51. Verghese, K.; Lewis, H.; Lockrey, S.; Williams, H. Packaging's Role in Minimizing Food Loss and Waste Across the Supply Chain. *Packag. Technol. Sci.* **2015**, *28*, 603–620. https://doi.org/10.1002/pts.2127
52. Feng, C.; Sun, K.; Zhang, Y.; Liang, R.; Mao, Y.; Hopkins, DL; Zhu, L.; Luo, X.; Yang, X. Differentiated application of oxygen levels for the preservation of high-oxygen packaged beef based on initial microbial contamination. *Meat Sci.* **2025**, *225*, 109803. https://doi.org/10.1016/j.meatsci.2025.109803
53. Mukta, S.; Updegraff, KM; Early, MR; Curtzwiler, GW; Vorst, KL Sustainability and "food mileage" of ground beef packaging in the beef industry from post-harvest to retail display. *Meat Sci.* **2026**, *232*, 109993. https://doi.org/10.1016/j.meatsci.2025.109993
54. Poveda, A.; Krell, J.; Heinz, V.; Terjung, N.; Tomasevic, I.; Gibis, M. The Use of MALDI-TOF MS for Microbial Identification of Discolored Vacuum-Packaged Beef. *J. Food Sci.* **2025**, *90*, e70591. https://doi.org/10.1111/1750-3841.70591

Article licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (http://creativecommons.org/licenses/by-nc-sa/4.0/)