Conceptualising Freshness in the Postharvest Fresh Vegetable Supply Chain: A Multidimensional Framework of Freshness-Influencing Factors

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ABSTRACT

Fresh vegetables undergo quality changes from harvest to retail, yet postharvest freshness is often represented through individual indicators such as appearance, temperature, or remaining shelf life. This conceptual paper develops a multidimensional framework to explain how product condition is retained or lost across the postharvest supply chain. Drawing on postharvest science and perishable-product logistics, it organises eight freshness-influencing factors into four dimensions: initial product condition (time of harvest; product quality and condition), environmental control (storage conditions; temperature control), process integrity (supply chain handling; contamination control), and logistics performance (mode of transportation; delivery time). Postharvest freshness is defined as the degree to which a fresh vegetable retains the sensory, physical, and nutritional attributes expected at retail purchase as it moves through the postharvest chain. Contamination control is considered alongside freshness retention, while microbiological safety remains a separate assessment. The framework proposes that freshness reflects initial condition and accumulated exposures, and that deterioration at an earlier stage may limit the benefit of later interventions. Ten conceptual propositions describe the proposed factor relationships, cross-dimensional interactions, and accumulated losses. A research agenda outlines how the framework could be measured and tested across vegetable types and supply chain settings, including those with limited refrigeration. The framework provides a basis for future freshness measurement and its potential use in logistics decisions; its dimensions, factor weights, and product-specific thresholds require empirical validation.

Keywords: postharvest freshness; fresh vegetables; conceptual framework; supply chain logistics; freshness measurement

INTRODUCTION

Once harvested, fresh vegetables remain biologically active. Respiration, transpiration, and other postharvest processes can progressively alter their condition. Handling, storage, and transportation conditions can influence the rate at which product quality deteriorates [1], [2]. Consumers describe the freshness of fruits and vegetables using both sensory and non-sensory characteristics, including perceptions related to time and distance from

production [3]. Postharvest and logistics research also examines changes in product condition through measures such as quality deterioration and temperature exposure [1], [2].

Deterioration before retail can reduce the marketable quantity of vegetables and contribute to food loss. Reducing such losses may improve food availability and, depending on where the reduction occurs, producers' income [4]. Inadequate storage facilities and transport infrastructure can make postharvest loss prevention more difficult [4].

Together, these perspectives suggest a need to connect product condition with the sequence of conditions experienced throughout the postharvest chain. A single measure, such as appearance or temperature, captures one aspect of product condition or exposure but does not, on its own, describe every process contributing to deterioration [1], [3]. Storage and transportation conditions affect the same product over successive stages [1], [2]. Research on quality-driven routing further shows that elapsed time and temperature changes during transport can affect the quality delivered to customers [5]. The present paper builds on these contributions by considering freshness in relation to initial product condition and subsequent postharvest exposures.

This paper addresses the following research question: What constitutes postharvest freshness in a fresh vegetable supply chain, and how do operational factors jointly influence its retention? It proposes a framework that organises eight freshness-influencing factors into four dimensions: time of harvest and product quality and condition (*initial product condition*); storage conditions and temperature control (*environmental control*); supply chain handling and contamination control (*process integrity*); and mode of transportation and delivery time (*logistics performance*). The framework connects product condition with postharvest practices and exposures from harvest to retail. It is intended to guide subsequent empirical measurement and optimisation.

The paper has three objectives: (1) to clarify the meaning and boundaries of postharvest freshness; (2) to organise its principal influencing factors into a multidimensional framework; and (3) to develop conceptual propositions and a research agenda for measuring and validating the proposed framework.

Conceptual Method

This paper uses a literature-based conceptual approach to develop a framework of postharvest freshness in fresh vegetable supply chains. It brings together perspectives from postharvest science, fresh-produce quality, food supply chain management, cold-chain control, and perishable-product logistics. Research on intelligent food logistics and the routing of perishable goods shows how product condition can inform operational decisions [6], [7]. These perspectives are synthesised to develop a conceptual framework, consistent with the purpose of an integrative literature approach [8].

Literature was considered for its relevance to the postharvest journey of fresh vegetables from harvest to retail. Studies of other fresh produce were considered where their postharvest or logistics mechanisms could reasonably apply to vegetables. The synthesis was guided by three questions: which mechanisms affect product condition after harvest; which observable or controllable supply chain practices influence that condition; and how product condition can be represented in freshness measurement or logistics decisions.

The unit of analysis is the postharvest journey of fresh vegetables from harvest to retail. Potential factors were considered when they could influence product condition or its rate of deterioration after harvest and could be linked to an observable or controllable supply chain practice. Related factors were grouped according to their principal mechanism of influence, yielding four proposed dimensions and eight freshness-influencing factors. Their distinctiveness, relative importance, interactions, and product-specific thresholds require empirical validation.

The framework focuses on fresh vegetables, with particular relevance to highly perishable leafy vegetables. Preharvest production, household storage, processing into minimally processed products, and formal food safety risk assessment fall outside its primary scope.

Literature Gap And Conceptual Positioning

Previous studies examine postharvest product condition from different perspectives. Keeping quality has been modelled in relation to initial quality and subsequent storage and distribution conditions [9]. Quality deterioration has been incorporated into vehicle routing alongside transportation cost and emissions [5]. Postharvest technologies for preserving the quality of fruits and vegetables have also been reviewed [1]. Other research connects monitored product condition with logistics decisions [6] and examines sensing, environmental control, and coordination across fresh-produce cold chains [2]. Table 1 compares the principal analytical themes of these studies with the proposed framework.

Table 1. Comparative Matrix of Freshness and Logistics Themes in Selected Studies and the Proposed Framework

Freshness element or analytical theme	**[9]**	**[5]**	**[1]**	**[6]**	**[2]**	**Proposed framework**
Initial product condition or quality	✓	✓	✓	✓	✓	✓
Harvest timing as a factor affecting subsequent quality	✓	×	×	×	×	✓
Storage or postharvest environmental control	✓	✓	✓	✓	✓	✓
Temperature–quality relationship	✓	✓	✓	✓	✓	✓
Handling or preservation practices	×	✓	✓	✓	×	✓
Hygiene or contamination control practices	×	×	✓	×	×	✓
Transport duration or delivery decisions	✓	✓	×	✓	✓	✓
Product quality changes across successive stages or distribution stops	✓	✓	×	✓	✓	✓
Quality-informed logistics decisions	×	✓	×	✓	✓	✓
Transport cost or carbon emissions considered	×	✓	×	×	✓	Outside the core framework
Eight factors organised into four proposed freshness dimensions	×	×	×	×	×	✓

Note: ✓ = substantively discussed or modelled within the study's scope; × = not substantively addressed within that scope. Classification reflects each study's analytical focus rather than every variable mentioned.

Table 1 shows that the selected studies address important aspects of postharvest product condition, including initial quality, temperature exposure, and decisions during distribution. However, their analytical aims differ,

and none of these five studies organises the eight specified freshness-influencing factors into the four dimensions proposed here for the harvest-to-retail journey of fresh vegetables. The gap identified in this comparison therefore concerns conceptual integration, rather than the absence of research on individual factors. The proposed framework treats freshness as a multidimensional and changing product condition shaped by exposures and practices across the postharvest chain. It provides a basis for subsequent empirical measurement and potential use in optimisation models.

Defining Postharvest Freshness

In this paper, postharvest freshness is defined as the degree to which a fresh vegetable retains the sensory, physical, and nutritional attributes expected at retail purchase as it moves through the postharvest supply chain. This is a proposed conceptual definition rather than one adopted unchanged from a single source. It has three features. First, freshness describes product condition relative to expectations at purchase; consumers describe freshness using both sensory and non-sensory characteristics [3]. Second, freshness changes over time because harvested vegetables remain metabolically active and may deteriorate after harvest [1]. Third, its assessment can draw on several product attributes and the conditions influencing them, rather than a single indicator [1], [10].

Sensory attributes may include appearance, colour, texture, crispness, aroma, and visible defects. Physical attributes include water status, firmness, structural integrity, and weight loss. Nutritional attributes concern the retention of vitamins and other bioactive compounds that may change during postharvest storage and distribution [1], [10]. Postharvest practices can also influence hygienic integrity and exposure to microbial hazards [11], [12]. Safety-related conditions are therefore considered alongside freshness in the proposed framework; however, visual freshness alone does not establish that a vegetable is microbiologically safe [11].

Freshness should be distinguished from related concepts. Quality encompasses a broad range of characteristics used to evaluate a product, whereas postharvest freshness, as defined here, focuses on the retention of its expected condition during the journey from harvest to retail [10], [12]. Shelf life is the period during which a product remains acceptable under specified conditions. Remaining shelf life estimates how much of that period is left, taking account of product attributes and environmental conditions experienced over time [13]. Freshness refers here to the changing condition of the product, rather than being identical to an estimate of remaining shelf life.

Four Dimensions And Eight Factors Of Postharvest Freshness

The proposed framework organises eight freshness-influencing factors into four dimensions. Initial product condition comprises time of harvest and product quality and condition. Environmental control comprises storage conditions and temperature control. Process integrity comprises supply chain handling and contamination control. Logistics performance comprises mode of transportation and delivery time. These dimensions describe factors that may influence the condition retained by fresh vegetables from harvest to retail. Their grouping and relative importance require empirical validation.

Initial Product Condition

Initial product condition establishes the quality available for preservation when vegetables enter the postharvest chain. It includes time of harvest and product quality and condition. Time of harvest encompasses both maturity at harvest and the timing of harvesting in relation to field and weather conditions. These choices can affect the condition of produce at harvest and its subsequent keeping quality. Appropriate harvest timing and prompt postharvest handling depend on the vegetable and its production conditions [9], [12].

Product quality and condition refer to the physiological and physical state of vegetables as they enter the postharvest chain. Maturity, mechanical injury, water status, and existing defects may influence how well a product withstands subsequent storage and transport [12]. Initial quality also affects the quality that can be retained later: postharvest controls may slow further deterioration, but they cannot restore quality already lost through damage or senescence [9], [12].

Environmental Control

Environmental control concerns the conditions surrounding vegetables after harvest. Storage conditions include relative humidity, airflow and ventilation, packaging, stacking, and the suitability of the storage facility. These conditions can affect moisture loss, heat removal, physical damage, and decay. Storage is therefore treated as a managed environment rather than merely as time spent in a facility [1], [12].

Temperature control is considered separately because temperature exposure continues through storage, transfers, and transport. Product temperature and the duration of exposure influence the rate of quality deterioration. A single temperature reading may miss fluctuations during handling or delivery; temperature history can provide a fuller account of product exposure [5], [6], [9]. Suitable temperatures and susceptibility to chilling injury differ among vegetables, requiring product-specific limits [9], [12].

Process Integrity

Process integrity concerns practices that protect vegetables as they pass between supply chain stages. Supply chain handling includes harvesting, sorting, grading, packaging, loading, unloading, stacking, and transfers between facilities or vehicles. Practices that reduce mechanical injury and unnecessary handling can help preserve product condition. The framework therefore considers both the quality of handling and the frequency with which vegetables are handled [1], [12].

Contamination control includes sanitation, personnel hygiene, clean containers and vehicles, suitable water, and measures to limit cross-contamination. It is included as a process that protects hygienic integrity alongside freshness retention. A vegetable may appear fresh while presenting a microbial safety hazard; visual condition must therefore not be treated as evidence of microbiological safety [11], [12]. The framework considers contamination control without equating freshness with food safety.

Logistics Performance

Logistics performance concerns the conditions and duration of movement between supply chain locations. Mode of transportation refers to the suitability of the vehicle and its protective arrangements for the vegetable, route, and operating conditions. Refrigeration or insulation, ventilation, loading arrangements, and protection from physical stress can affect the conditions experienced during transit. Vehicle choice should therefore be assessed alongside its capacity to protect product quality [5], [6], [12].

Delivery time is the elapsed period from dispatch to receipt, including travel, intermediate waiting, and delays. Its effect on retained quality depends on product characteristics and temperature exposure; journeys of the same duration need not result in the same quality loss [5], [9]. Delivery time should therefore be assessed together with product condition and temperature history, rather than inferred from distance alone. Freshness-oriented routing must consider the quality delivered to the recipient as well as the timing of delivery [5], [7], [14].

Proposed Conceptual Framework

Figure 1 presents the four proposed dimensions and their eight factors in relation to freshness retention and outcomes at retail. Solid arrows indicate proposed direct influences, while dashed connectors illustrate possible interactions among dimensions. These relationships, including their strength and product-specific thresholds, require empirical validation.

Three principles guide the interpretation of the framework. Accumulation means that a vegetable's condition at a given point reflects both its initial quality and the exposures experienced thereafter [6], [9]. Path dependence means that deterioration earlier in the chain may limit the quality that later interventions can preserve [9]. Complementarity proposes that temperature control, careful handling, timely delivery, and suitable transportation may work together to retain freshness; the nature and strength of these interactions remain to be tested [5], [6].

The proposed relationships need not be linear or fully compensatory. Temperature and exposure duration can affect the rate of deterioration, and unsuitable low temperatures can cause chilling injury in susceptible vegetables [9], [12]. Cooling or faster delivery may slow further deterioration without reversing damage already sustained. Suitable limits and exposure durations must therefore be established for the vegetable and operating conditions under study [9], [12].

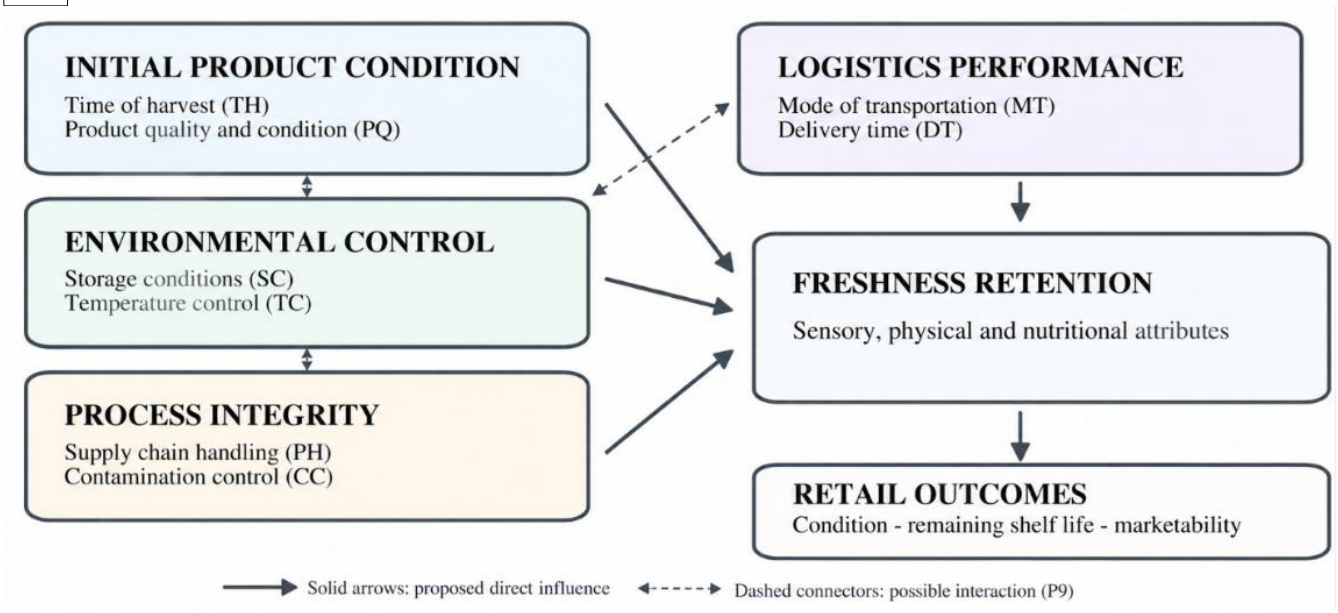


Figure 1. Multidimensional framework of postharvest freshness in fresh vegetable supply chains

Note: Solid arrows indicate proposed direct influences; dashed connectors illustrate possible interactions. All relationships require empirical validation.

Conceptual Propositions

Table 2 presents ten conceptual propositions derived from the proposed framework. P1–P8 correspond to its eight freshness-influencing factors. P9 concerns possible interactions among dimensions, while P10 concerns the accumulation of quality losses across postharvest stages. These propositions are intended for future empirical testing.

Table 2. Conceptual Propositions for Postharvest Freshness

Proposition	Statement
P1. Time of harvest	Appropriate harvest timing is positively associated with the retention of postharvest freshness.
P2. Product quality and condition	Better product quality and condition at entry into the postharvest chain are positively associated with subsequent freshness retention.
P3. Storage conditions	Storage conditions suited to the vegetable are positively associated with postharvest freshness retention.
P4. Temperature control	More continuous and product-appropriate temperature control is positively associated with the retention of postharvest freshness.
P5. Supply chain handling	Handling practices that reduce mechanical injury and unnecessary stress are positively associated with postharvest freshness retention.

Proposition	Statement
P6. Contamination control	More effective contamination control is positively associated with hygienic integrity during the postharvest journey. Its relationship with measured freshness should be assessed separately from microbial safety [11], [12].
P7. Mode of transportation	Transportation arrangements suited to the vegetable and route are positively associated with postharvest freshness retention.
P8. Delivery time	Shorter, more reliable delivery time is positively associated with postharvest freshness retention, conditional on product characteristics and temperature exposure.
P9. Cross-dimensional interaction	The association between an individual factor and freshness retention varies with conditions in other dimensions.
P10. Accumulated loss	Quality losses occurring earlier in the postharvest chain reduce the condition that can be retained through later interventions.

P9 suggests that the effect of one factor may depend on conditions in another dimension. For example, the effect of a delivery delay depends on the temperature experienced during that delay and the vegetable's sensitivity; equal delivery times therefore need not produce equal quality losses [5], [9]. P10 suggests that earlier losses may limit what later interventions can preserve. Unsuitable low temperatures may cause chilling injury, while severe physical damage or decay may reduce acceptability in ways that later cooling or faster delivery cannot reverse [9], [12]. Future studies should test time–temperature interactions, cumulative exposure across stages, and product-specific thresholds. When a validated quality limit is exceeded, favourable performance on other factors should not automatically compensate for that failure in a composite freshness score. Food safety criteria must be assessed separately from that score [11], [13].

Theoretical Contribution

The framework treats freshness as a changing product condition shaped by decisions and exposures throughout the postharvest chain. Appearance, temperature, and transit time each provide useful information, but their interpretation depends on initial condition and subsequent exposures [1], [6], [9]. Considering these elements together may improve explanations of freshness retention.

The four-dimensional structure links observable practices with product condition. Its eight factors identify conditions and practices that can be measured or managed, while the dimensions provide a common structure for examining different vegetables and supply chain arrangements. Indicators can be selected for each vegetable without assuming a universal deterioration pattern. Water loss and wilting may be especially relevant for leafy vegetables; firmness, colour, chilling injury, or decay may warrant greater emphasis for other commodities [9], [10], [12].

The framework also connects postharvest science with supply chain and optimisation research. Future studies could represent product condition with a validated freshness score or retention function and examine how storage and logistics decisions shape exposures. This offers a conceptual basis for investigating routing, scheduling, vehicle selection, and storage decisions informed by product condition [5], [6], [7], [14].

Practical Implications

For producers and collection centres, the framework draws attention to harvest timing and the condition of vegetables entering distribution. Wholesalers and retailers can monitor storage, handling, hygiene, and delivery alongside arrival condition. Transport operators can evaluate vehicle suitability and delivery speed together with temperature exposure and load protection.

To operationalise the framework, researchers could select an observable indicator for each factor: harvest timing; incoming product condition; storage humidity, ventilation, or duration; recorded product temperature and excursion duration; handling damage; sanitation compliance; vehicle protection; and elapsed delivery time. Indicators could be mapped to a documented 0–1 desirability scale using vegetable-specific reference ranges. Weights could be elicited through expert pairwise comparisons with consistency checks [15] and compared with weights estimated from outcome data when available. Scores could then be aggregated within and across dimensions, with indicators and weights reported alongside the composite score. This is a proposed measurement procedure, not a validated universal freshness measure.

Before operational use, the proposed score should be calibrated against measured arrival quality and, where feasible, remaining shelf life, then evaluated across routes, seasons, and commodities. Validated limits for severe quality damage and food safety should be applied as separate decision rules: a high weighted score cannot establish microbiological safety or cancel an unacceptable threshold exceedance [11], [13].

By identifying vulnerable stages, the framework may help target interventions that reduce avoidable losses. Whether this improves food availability or producers' income depends on where losses occur and how the costs and benefits of interventions are distributed [4].

The dimensions also apply where refrigeration is absent or unreliable. In ambient, informal, and rural supply chains, feasible controls may include harvesting during cooler periods, shade, ventilation, careful stacking, clean containers, shorter waiting times, and evaporative cooling where suitable [12]. Temperature exposure can be monitored without requiring refrigerated vehicles. Local studies should estimate product-specific losses and feasible controls before transferring weights or thresholds from formal cold chains.

Research Agenda

Table 3. Research Agenda for Framework Validation and Application

Research area	Guiding question	Possible approach
Construct structure	Do the eight factors form four meaningful and distinguishable dimensions across different vegetable groups?	Expert assessment; field data; comparison of formative and reflective measurement specifications
Freshness measurement	Which sensory, physical, and nutritional indicators best represent retained freshness for a specified vegetable?	Product measurements; expert panels; consumer evaluation
Food safety assessment	How should contamination-control practices and microbiological safety criteria be assessed alongside freshness?	Hygiene audits; microbiological testing; separate safety decision rules
Time–temperature effects	How do exposure duration, temperature history, and temperature excursions affect quality retention?	Temperature sensors; longitudinal product measurements; product-specific deterioration models
Cross-stage effects	How does early deterioration affect the benefit of later controls, and where do irreversible losses occur?	Longitudinal supply chain studies; staged handling and storage experiments
Stakeholder perspectives	Do supply chain actors differ in how they judge the importance and feasibility of the eight factors?	Interviews; Delphi panels; AHP or fuzzy AHP
Operational integration	How can a validated freshness measure inform routing, scheduling, vehicle	Mixed-integer optimisation; goal programming; scenario analysis

Research area	Guiding question	Possible approach
	selection, and trade-offs involving cost and emissions?	
Context transferability	How do climate, infrastructure, route length, and supply chain form change the framework relationships?	Comparative case studies across formal, ambient, informal, and rural supply chains

Limitations

The framework is intentionally focused and does not claim that the eight factors exhaust every determinant of freshness. Cultivar, preharvest practices, packaging technology, atmospheric composition, ethylene management, market display, and consumer storage may require explicit treatment in particular settings. The proposed relationships are directional but not quantified. Empirical studies must test whether the four dimensions are distinct, whether some factors operate as moderators or mediators, and whether nonlinear or threshold effects provide a better representation than additive models.

The framework also separates conceptual structure from product-specific measurement. This preserves transferability, but it means that the meaning of an acceptable temperature, delivery duration, or quality score cannot be specified without a defined vegetable, route, and market requirement. In particular, a composite score requires validation against independent product measurements; the procedures proposed here for determining weights and critical limits do not constitute estimates established by this conceptual study.

CONCLUSION

Postharvest freshness is proposed here as a multidimensional and changing product condition shaped by initial quality and exposures from harvest to retail. The framework organises eight freshness-influencing factors into four dimensions: initial product condition, environmental control, process integrity, and logistics performance. It offers a structure for developing and subsequently validating freshness measures and for examining how product condition can inform supply chain decisions. Future research should test the proposed dimensions, cross-stage interactions, product-specific thresholds, and applicability across supply chains with different resources and operating conditions.

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