

Analysis on Quality Improvement Mechanism of Live Fish Under Two-level Mode of Production Warehouse and Urban Warehouse

Xinyu Zhu

Nanjing Foreign Language School, Nanjing, Jiangsu, China

Abstract: Quality degradation during the distribution of live fish represents a critical bottleneck hindering the high-quality development of the aquatic product industry. Based on a two-tier warehousing system comprising origin warehouses and urban warehouses, this paper systematically examines the intrinsic mechanisms underlying the improvement of live fish quality. The study argues that the dual-warehouse framework implements comprehensive, end-to-end intervention addressing live fish's physiological stress, metabolic burden, and immune system fluctuations through three distinct pathways: precise environmental control, coordinated transportation optimization, and ecological rehabilitation during temporary holding. The enhancement of fish quality is not merely the additive application of technologies at individual stages, but rather a systemic benefit arising from the functional differentiation and dynamic coupling between the origin and urban warehouses. Under this two-tier model, the origin warehouse serves the functions of source acclimation and ecological buffering, while the urban warehouse is responsible for final-stage rehabilitation and quality stabilization; together, they form a complementary governance network across both temporal and spatial dimensions, ultimately establishing a closed-loop system for maintaining the fresh quality of live fish from the moment they leave the water until they reach the consumer's table.

Keywords: Origin Warehouse; Urban Warehouse; Live Fish Distribution; Quality Improvement.

1. Introduction

Fresh live fish hold an irreplaceable position in the consumer market due to their tender texture and comprehensive nutritional value; however,

the issue of quality deterioration during their distribution process has long been a concern for both the industry and academia. The traditional distribution chain for live fish is lengthy and subject to significant environmental fluctuations; throughout the stages of fishing, transportation, and temporary holding, the fish are exposed to multiple stressors, which sequentially activate various quality-degrading pathways-such as muscle glycogen depletion, lactic acid accumulation, and immune suppression. The dual-warehouse storage model-comprising both origin warehouses and urban warehouses-has rapidly gained traction in the fresh produce supply chain; its core principle lies in transforming warehouse functions from passive storage into proactive quality intervention nodes. Nevertheless, existing research has predominantly focused on the technical optimization of individual warehouses or improvements to the transportation phase, lacking in-depth exploration of the systematic mechanisms underlying quality enhancement within a dual-warehouse framework. This paper seeks to move beyond a "technical checklist" approach and, from the perspective of functional differentiation and collaborative governance between warehouses, reveals the intrinsic mechanisms by which the dual-warehouse model enhances the quality of live fish, thereby providing theoretical support for the development of aquatic product distribution theory and practical industrial applications.

2. Quality Governance Logic for Tier 1 and Tier 2 Warehousing Architectures

2.1 Functional Differentiation of Storage Spaces and the Spatiotemporal Reconfiguration of the Quality Intervention Chain

The origin warehouse and the urban warehouse perform fundamentally distinct quality management functions within the secondary supply chain structure; this functional

differentiation constitutes the primary prerequisite for the quality improvement mechanism. Located near aquaculture waters, the origin warehouse's core mission is to facilitate a smooth transition of live fish from the farming environment to the artificial temporary holding environment, with a focus on mitigating fishing-related stress, damage incurred during grading and screening, and initial metabolic disturbances. The urban warehouse, situated near consumer endpoints, primarily addresses the issues of cumulative physical fatigue and diminished immune function in fish following long-distance transportation, striving to restore the fish's homeostasis within the shortest possible timeframe. Together, these two warehouses form a quality intervention chain-comprising "front-end acclimation-intermediate transportation-end-point recovery"-which disperses the stress load, typically concentrated during traditional distribution processes, across different stages for gradual resolution. This spatiotemporal restructuring ensures that the intensity of intervention at each stage can be kept within the threshold tolerable by the fish, thereby avoiding the diminishing marginal returns associated with excessive processing at a single stage. More importantly, this functional differentiation between the warehouses is not a static division of labor but is dynamically adjusted based on the species of live fish, the transportation distance, and seasonal variations, thereby creating a flexible quality management network. The profound value of this approach lies in its recognition of the cumulative and irreversible nature of live fish quality deterioration, thereby providing both temporal buffer and spatial redundancy for quality preservation at the supply chain level.

2.2 Stress Accumulation Inhibition Effect under a Two-Tier Buffering Mechanism

Stress accumulation is the primary driving force behind the deterioration of live fish quality; the two-tier storage architecture incorporates two distinct buffering interfaces into the time-series representation of stressors^[1]. The first buffering layer occurs at the origin warehouse, where live fish undergo their initial post-harvest rest and recovery period-during which certain reversible stress markers, such as cortisol concentration and blood glucose levels, are initially corrected. The second buffering layer emerges at the urban

warehouse; upon arrival, the fish are given a second opportunity for recovery in a new water environment, allowing the oxidative stress products generated by the prolonged transportation journey and density stress to be gradually eliminated. The combined effect of these two buffering layers disrupts the simplistic additive pattern of stress factor accumulation over time, giving rise instead to an alternating "stress-recovery-restress-recovery" cycle that prevents the fish from ever falling into an irreversible state of physiological exhaustion. From a cybernetic perspective, this two-tier buffering mechanism is equivalent to introducing a feedback regulation node into the quality control system-where each recovery phase provides resilience redundancy for the subsequent transportation stage. This mechanism is particularly well-suited for live fish, a commodity highly sensitive to continuous perturbations, as a single prolonged stress event often causes more severe tissue damage than multiple brief stress events; the two-tier architecture precisely breaks down continuous stress into discrete, self-repairable units.

2.3 Quality Information Transmission and Response Closed-Loop in Inter-warehouse Collaboration

The secondary warehousing architecture serves both as a physical distribution system and as a network for acquiring, transmitting, and responding to quality-related information. During the temporary holding phase at the origin warehouse, the origin warehouse successfully collects core quality data-such as the initial vitality, feeding behavior, and water quality adaptability of live fish-and transmits this information in real time to the urban warehouse via a digital management system. This enables the urban warehouse to predict the physiological status of the fish shipment before it arrives, allowing it to develop customized, differentiated recovery strategies for the batch. For instance, for batches monitored by the origin warehouse that exhibit high stress responses, the urban warehouse can proactively reduce the temporary holding density, adjust the salinity to an appropriate level, and extend the static holding duration. Subsequently, the urban warehouse can feed back data-including survival rates, visual inspection scores, and behavioral vitality-to the origin warehouse to evaluate the effectiveness of the front-end acclimation strategy, thereby

forming a "front-end prediction-end-point adaptation, bidirectional refinement" quality response closed-loop. The inherent value of this information closed-loop lies in the transformation of quality improvement from a unidirectional operational process into a cyclical iterative one; each distribution cycle generates new knowledge and drives both warehouses to optimize their respective intervention parameters. Once this collaborative mechanism is fully operational, quality improvement is no longer contingent upon isolated technological breakthroughs at a single warehouse, but rather stems from the increasingly evident systemic improvement efficacy arising from the inter-warehouse coupling relationships^[2].

3. Environmental Regulation and Physiological Homeostasis Remodeling Mechanisms

3.1 Precision Allocation Strategy for Water Quality Parameters by Warehouse

Water quality is the most direct external determinant of live fish quality; the two-stage storage system enables the implementation of differentiated water quality management strategies across the two storage phases based on their respective objectives^[3]. The water quality management at the origin storage phase focuses on simulating the fundamental characteristics of the raw water used in aquaculture, thereby reducing the fish's sensitivity to abrupt environmental changes. Key parameters-such as temperature, dissolved oxygen levels, and pH-are maintained near the baseline values of the culture ponds; simultaneously, salinity is moderately increased to leverage the calming effect of osmotic pressure regulation. In contrast, the urban storage phase is designed around restoration objectives; its water quality parameter settings are geared toward facilitating the excretion of metabolic waste and accelerating the replenishment of energy reserves. Here, the temperature is typically maintained at a slightly lower level to reduce the basal metabolic rate, while the total ammonia nitrogen concentration is strictly kept below a specified threshold using microfiltration and protein separation technologies. The distinction between these two water quality management strategies is not arbitrary but is based on the primary physiological challenges faced by live fish at different stages of their lifecycle: the

origin storage phase prioritizes a "smooth transition," whereas the urban storage phase is oriented toward "efficient restoration." It is important to note that this precise compartmentalization does not imply the use of two entirely separate sets of standards; rather, it achieves a gradual transition of parameters through the design of a transitional zone, preventing excessive differences in water quality between the storage phases from becoming new sources of stress. Such a sophisticated, zoned water quality management approach can only be fully realized under the spatial separation conditions provided by the two-stage system; a single-storage model is inadequate for accommodating such a functionally differentiated water environment design.

3.2 The Coupled Regulation of Temperature and Dissolved Oxygen Plays a Directed Role in Governing Energy Metabolism

Temperature and dissolved oxygen are the two core variables that influence the energy metabolism pathways of live fish; the secondary storage architecture enables the phased reconfiguration of their coupled relationship through independent control of the two storage compartments^[4]. At the origin storage facility, water temperature regulation focuses on synergizing with dissolved oxygen levels to reduce the energy expenditure associated with fish activity; appropriate dissolved oxygen levels combined with suitable temperatures help maintain aerobic metabolism within an efficient range, thereby reducing the lactic acid load generated by anaerobic glycolysis. At the urban storage facility, given that the liver glycogen reserves of the fish have been significantly depleted following transportation, the coupled temperature-dissolved oxygen strategy shifts toward accelerating fat mobilization and gluconeogenesis, providing an energetic foundation for immune system recovery. The distinct combination of temperature and dissolved oxygen levels at the two storage compartments represents a deliberate intervention to guide the direction of the fish's energy allocation: during the origin storage phase, energy is directed toward the synthesis of stress-resistant proteins; during the urban storage phase, energy is directed toward tissue repair and the production of immune-related factors. This targeted physiological approach is based on the plasticity of fish energy metabolism, and the

secondary storage architecture precisely provides a temporal window for implementing these regulatory strategies in a staged manner. When the temperature-oxygen coupling parameters for the two storage compartments are configured in a systematic rather than a random manner, the energy consumption curve for live fish throughout the entire process-from removal from water to placement on the market-can be significantly flattened, thereby avoiding regulatory conflicts that arise when attempting to achieve all desired outcomes within a single storage compartment.

3.3 Neuroendocrine Regulatory Pathways under the Influence of Hydrochemical Signaling

Dissolved chemical factors in water exert a direct regulatory effect on the neuroendocrine system of live fish; the secondary storage model creates the conditions for the systematic application of such intervention strategies^[5]. The origin storage facility can add mineral elements-such as magnesium ions and calcium ions-at appropriate concentrations into the water body; upon absorption by the gill epithelium and entry into the circulatory system, these elements act on the hypothalamic-pituitary-kidney axis, thereby inhibiting the excessive release of cortisol. The controlled use of low-concentration anesthetic adjuvants at the origin storage facility can effectively dampen the fish's sensitivity to external disturbances, reducing the frequency of stress response activation at the neural level. The urban storage facility, on the other hand, focuses on utilizing aquatic chemical signals to promote the synthesis of endogenous sedative substances-such as melatonin-and to regulate the fish's circadian rhythm, thereby accelerating time-zone adaptation and the restoration of its physiological cycle. These chemical intervention strategies are not employed in isolation but are integrated into a composite signaling environment alongside the aforementioned temperature and dissolved oxygen parameters, collectively influencing the fish's neurotransmitter release patterns and hormone secretion rhythms. The value of the secondary storage system lies in the fact that each storage facility can independently design chemical signaling formulations tailored to its specific stage of the fish's lifecycle; moreover, these formulations are interconnected, forming a neuroregulatory gradient of

"pre-sedation-intermediate maintenance-post-recovery," ensuring that the fish remains within a controllable physiological activation range throughout its entire distribution journey and thereby preventing tissue damage resulting from dramatic fluctuations in hormone levels.

4. Temporary Housing Ecology and the Activation Mechanism for Organismal Self-Repair Capacity

4.1 Release of Social Pressure and Improvement of Behavioral Welfare under Density Gradient Management

The population density of live fish in temporary holding containers directly influences their social interaction stress and spatial behavior patterns. The dual-stage storage model evolves density management from a broad "low-density principle" into a sophisticated gradient-based design approach. During the origin warehouse phase, a gradually decreasing density strategy is employed: after a brief period of high-density aggregation at the onset of harvesting, the fish are swiftly distributed across multiple low-density temporary holding tanks. This transition not only meets operational efficiency requirements but also minimizes the duration of high-density stress. Upon entering the urban warehouse, density management is further tailored based on the individual size and vitality level of the fish; highly active individuals are appropriately dispersed to reduce the frequency of chasing and aggression, while less active individuals are moderately concentrated to enhance the group's sense of security. The underlying mechanism of this density gradient management is to mitigate social stress in fish-under excessive density, visual contact and lateral line sensing between individuals can become persistent environmental stressors, whereas moderate density provides the fish schools with normal social feedback and behavioral buffer space^[6]. The role played by this dual-stage architecture is that the density standards for the two warehouses do not need to be identical: the origin warehouse can tolerate slightly higher densities to achieve source-level aggregation efficiency objectives, while the urban warehouse maintains extremely low densities to ensure optimal end-product quality; together, these two stages create a mechanism for sharing the density-related burden across the

overall distribution timeline.

4.2 Alignment of Feeding Frequency with the Temporal Pattern of Nutritional Status Recovery

Live fish subjected to long-distance transportation often find themselves in a state of negative nitrogen balance and energy deficit; therefore, the feed supplementation strategy during their temporary storage in urban facilities directly influences the material foundation upon which their self-repair capacity is built. Under a dual-storage system, the origin facility may implement feed restriction or cessation of feeding to reduce metabolic burden and prevent the accumulation of excretory waste; however, this simultaneously triggers the utilization of the fish's endogenous energy reserves. Consequently, feed supplementation in the urban facility must be precisely tailored to the fish's state of deficiency, following a temporal sequence-"first restore osmotic balance, then activate digestive function, and finally gradually increase feeding rates"-and should consist of high-quality protein sources that are easily digested and absorbed, along with comprehensive multivitamin complexes. The technical challenge of this temporal alignment lies in accurately determining the severity of the deficiency in each batch; the feeding behavior records transmitted from the origin facility provide the exact basis for making such decisions. The combined feed management strategy-namely, "feed restriction and intestinal cleansing at the origin facility followed by programmed supplemental feeding at the urban facility"-not only mitigates the risk of water quality deterioration associated with continuous feeding throughout the entire transport process but also ensures that the fish complete the replenishment of their critical nutritional reserves prior to shipment^[7]. The activation of an organism's self-repair capacity depends on an adequate supply of substrates, and the precise spatiotemporal accuracy of such substrate supply represents a unique advantage afforded by this dual-storage architecture.

4.3 The Time Dynamics of Rest Duration and Immune Function Recovery

The recovery of immune function in live fish follows specific temporal dynamics; the dual-warehouse architecture provides ample and continuous temporal support for this natural

process. The resting period at the origin warehouse initially alleviates the acute immunosuppression induced by harvesting, leading to an increase in phagocytic cell activity and lysozyme levels; however, full immune system reconstruction still requires a longer duration^[8]. The subsequent resting period at the urban warehouse precisely bridges the time gap between the initial recovery phase and the functional restoration phase. The allocation of resting periods across the two warehouses is based on the phased characteristics of the immune recovery curve: the early recovery phase requires a stable environment to restart immune gene transcription, whereas the late recovery phase is conducive to introducing mild environmental stimuli to enhance immune memory. This dual-warehouse approach allows the entire recovery period to be divided into two spatially separated but temporally continuous implementation phases, thereby avoiding the forced shortening of the resting period at a single warehouse due to turnover pressures, as well as preventing disruptions to the recovery process caused by abrupt environmental changes at the intermediate warehouse. When the total cumulative resting period across both warehouses exceeds a critical threshold, key biomarkers-such as lysozyme levels, complement activity, and immunoglobulin concentrations-in the fish can rebound to levels approaching those observed in their original farming ponds. This "source-initiation-end-completion" relay-based resting model provides a robust immune safeguard for the final quality of live fish.

5. Conclusion

The enhancement of live fish quality through the two-tier warehouse model-comprising origin warehouses and urban warehouses-is fundamentally achieved by upgrading traditional, single-point, passive warehousing practices into a distributed, proactive quality intervention system. Research indicates that the advantage of this two-tier architecture lies not only in the expansion of physical space but also in the innovative governance logic arising from the functional differentiation between origin and urban warehouses: the origin warehouse focuses on stress mitigation and source-level acclimation, while the urban warehouse is dedicated to fatigue recovery and quality stabilization; together, these two components form a

comprehensive quality assurance chain through information coordination, environmental fine-tuning, and operational integration. Three core mechanisms-stress accumulation suppression, energy metabolism guidance, and immune function reconstruction-address the respective quality bottlenecks at the upstream, midstream, and downstream stages of the distribution chain; through the alternating intervention of both warehouse types, a tiered protective barrier is established. The theoretical contribution of this study lies in revealing that quality improvement is not merely the sum of isolated, locally optimal operations, but rather the emergent structural efficacy of the entire two-tier system. This insight facilitates a paradigm shift in live fish distribution research-from a purely technical improvement-oriented perspective to one grounded in systemic governance-and provides a unique reference point derived from the aquatic products sector for the theory of quality management in fresh produce supply chains.

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