



Review

Current Status and Countermeasures for the Development of Cold Chain Logistics for Agricultural Products in Western China

Yitong Yu¹ , Yanlei Li^{2,3,*} 

¹College of Economics and Management, Shanghai Ocean University, 201306 Shanghai, China

²Mechanical and Electrical Engineering College, Beijing Polytechnic College, 100042 Beijing, China

³Institute of Food Science and Technology, Chinese Academy of Agricultural Sciences, Key Laboratory of Agro-Products Quality and Safety Control in Storage and Transport Process, Ministry of Agriculture and Rural Affairs, 100193 Beijing, China

*Correspondence: liyanlei2021@163.com (Yanlei Li)

Academic Editor: Corinna Kehrenberg

Submitted: 11 February 2026 Revised: 24 March 2026 Accepted: 1 April 2026 Published: 8 July 2026

Abstract

Cold chain logistics plays a critical role in ensuring the quality and safety of temperature-sensitive agricultural products, including meat, vegetables, and fruits. Focusing on Western China and the associated region-specific agricultural products, this study reviews the current state of development of cold chain logistics technologies and equipment, encompassing packaging, transportation, pre-cooling, storage, preservation, and sterilization. Moreover, this study discusses the key strengths and limitations of the current system and proposes targeted policy and operational recommendations. The study also analyzes the adoption of emerging Internet of Things (IoT) technologies in core functions, such as information management, traceability, and real-time monitoring. Additionally, the study highlights the effectiveness of metaheuristic and hybrid algorithms in optimizing cold chain distribution routes. In the future, agricultural cold chain logistics in Western China are expected to evolve into a more intelligent, standardized, and internationally interconnected system. Supported by geographic endowments and policy incentives, this transformation is expected to help convert regional production advantages into sustained economic competitiveness.

Keywords: Western China; cold chain logistics; IoT technology; route optimization

1. Introduction

1.1 Strategic Significance of Agricultural Products in Western China

Western China covers extensive territories across the Loess Plateau, the Qinghai–Tibet Plateau, and the Yunnan–Guizhou Plateau, including the Xinjiang and the Sichuan Basins. With a total area of approximately 6.86 million square kilometers [1], the region accounts for 71% of China's land area and has a resident population of around 380 million [2]. The geographical scope of Western China, as defined by China's tripartite regional classification of eastern, central, and western zones, is illustrated in Fig. 1 (Ref. [3]).

The region exhibits an elevation gradient of up to 7000 m and climatic zones ranging from tropical to subarctic. These distinctive geographical conditions have supported the production of unique local agricultural products such as Linzhi walnuts, wild ancient tea trees from the upper Min River, and a local breed of black pigs with yellow bristles. This not only highlights the competitiveness of Western China's distinctive agriculture but also underscores its strategic importance to China's food and industrial resilience. Building on this foundation, Sichuan and Yunnan have capitalized on their distinct climatic advantages of humid subtropical valleys and low-latitude plateaus, respectively. Currently, leveraging its strategic advantage as a

corridor along the Belt and Road, Xinjiang has become a key hub on the Central Asia–Europe agricultural corridor [4].

1.2 Development Status of Agricultural Products in Western China

The agricultural products examined in this study include meat, vegetables, and fruit products. As of 2024, China's total meat output, including pork, beef, mutton, and poultry, has reached 97.80 million tons [5]. As a national meat production base, Western China has established a large-scale, specialized meat production pattern. Its plateau-adapted livestock breeds such as yaks have become key sources of meat supply in this region [6].

China's western regions leverage unique geographical and climatic conditions such as plateaus and mountains. These regions have developed a distinctive vegetable industry characterized by high-quality and diverse specialties. Take Fuling in Chongqing as an example: Local pickled mustard greens rank among the world's three most renowned pickled vegetables alongside German sauerkraut and European pickled cucumbers.

In terms of specialty fruits, Sichuan Province is well known for Anyue lemons and many other related agricultural products [7]. Yunnan Province excels in coffee bean production, with cultivation primarily concentrated in five core regions: Pu'er City, Lincang City, Baoshan City, De-



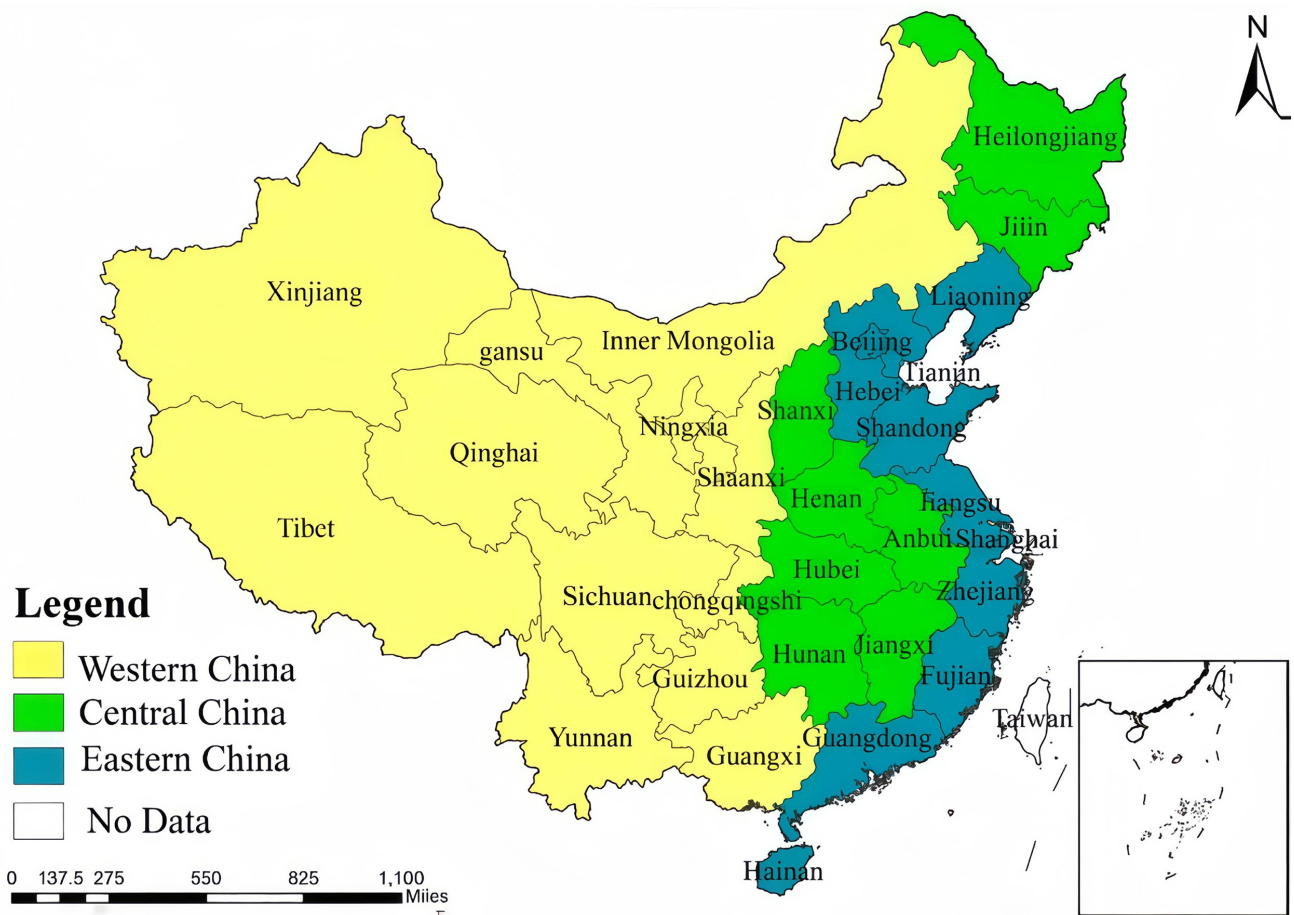


Fig. 1. Regional division map of Eastern, Central, and Western China [3].

hong, and Xishuangbanna. In 2021, Yunnan Province accounted for 0.82% of the global total in terms of cultivated area and 1.08% in terms of green bean production. In 2022, this province alone accounts for over 98% of China’s total coffee output. Therefore, the province maintains a dominant position within China’s coffee production industry [8]. Shaanxi is a leader in high-quality fruit. Its apple output reaches 11.85 million tons, accounting for 27% of China’s total. Moreover, its kiwifruit yield of 1.16 million tons represents 35% of the national production, marking both as “national firsts” in industry competitiveness [9]. In contrast, Yunnan Province is situated on a low-latitude plateau where vegetable-growing areas are distributed at various altitudes, following a topography that slopes northwest to southeast in steps. This natural terrain provides a distinct advantage for producing off-season fruits [10]. In this context, this paper systematically reviews the current status, core technologies, and countermeasures for agricultural product cold chain logistics in Western China. These technologies include packaging, transportation, pre-cooling, storage, preservation, and sterilization. The paper also analyzes the advantages and limitations of these technologies and explores the integration of emerging Internet of Things (IoT) technologies with metaheuristic algorithms,

with the aim of providing a comprehensive strategic reference for researchers and policymakers in Western China. To ensure the authority of this review and the rigor of its conclusions, we implemented a structured literature search strategy across multiple databases. Fig. 2 below clearly illustrates the process of literature identification, screening, and inclusion for this review.

2. Current Status of Agricultural Products Logistics Development in Western China

2.1 Advantages of Agricultural Products Logistics Development in Western China

Cold chain logistics is a systematic approach that maintains specified temperature ranges (typically 0–4 °C) throughout the entire lifecycle of temperature-sensitive products, from production and storage to transportation, processing, and distribution, to preserve physicochemical stability and product quality [11]. Currently, Western China is leveraging its geographical and policy advantages to transform cold chain logistics from a developmental weakness into a key pillar for participating in the Belt and Road market.

Northwest China is located at the forefront and core of the Eurasian Economic Zone. Encompassing Shaanxi

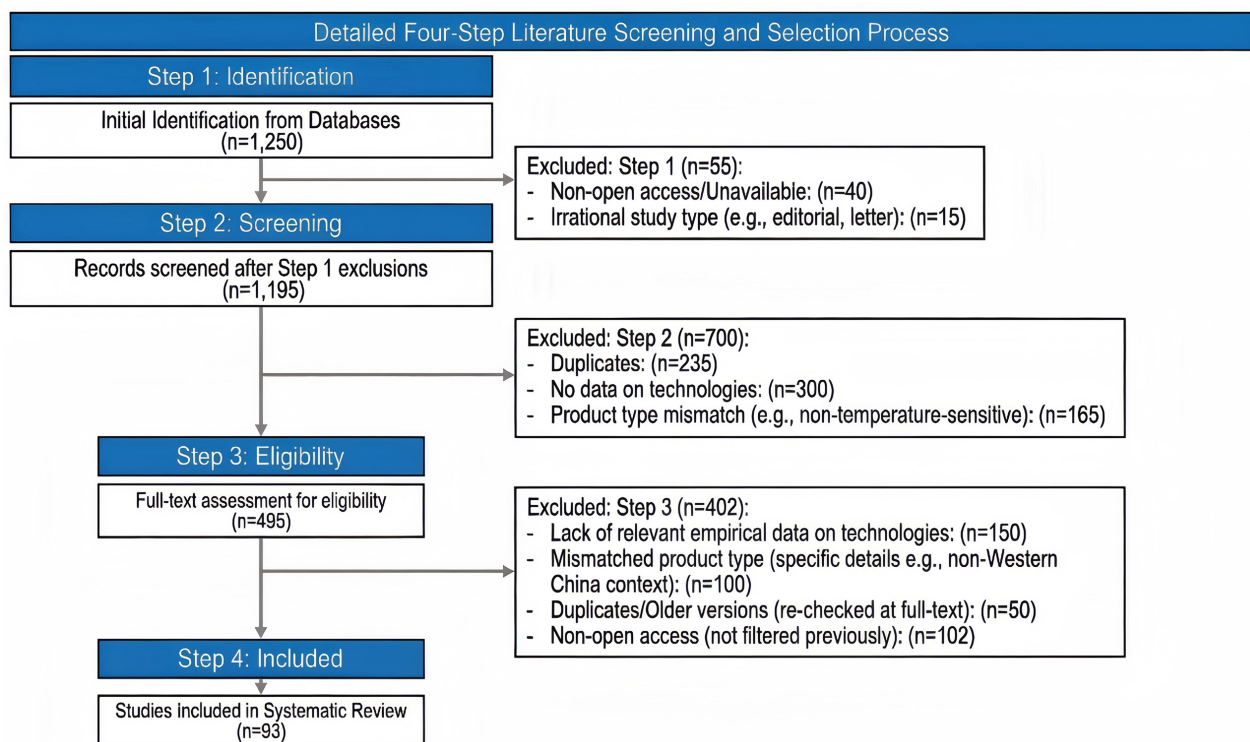


Fig. 2. Flowchart of main literature screening and selection process.

Province, Gansu Province, Ningxia Hui Autonomous Region, Qinghai Province, and Xinjiang Uygur Autonomous Region, this area possesses significant locational advantages, with the potential to serve as the future pivotal corridor of Eurasia. To drive regional economic growth and deepen the implementation of the Belt and Road Initiative, Chinese government has introduced multiple preferential policies to attract foreign investment, fostering a favorable institutional environment. Building on this foundation, the government and relevant enterprises are actively introducing advanced cold chain logistics technologies and facilities, laying a solid material foundation for establishing a specialized and distinctive cold chain logistics system in Northwest China [12].

With Chongqing Municipality at its core, Southwest China—which also encompasses Sichuan, Guizhou, Yunnan, and Tibet—possesses unique strategic advantages in agricultural logistics. As the hinterland of the Western Land-Sea New Corridor, it achieves efficient connectivity with Beibu Gulf Port and China–Europe Railway Express via three main corridors, forming an intermodal transport network that reduces cross-border logistics costs. The core coverage area encompasses major agricultural production zones like Yunnan and Guizhou, while the extended service area connects to Lanzhou and Urumqi, linking to the Silk Road Economic Belt. Through Kunming, it extends overland to Southeast Asia, establishing a cold chain logistics corridor serving Southeast Asian and broader regional markets.

The dual hubs of Chengdu and Chongqing provide logistics operation and coordination centers, complemented by Southwest China’s comprehensive transportation network and significant economies of scale in cold chain demand [13]. In terms of policy advantages, Sichuan, Chongqing, and Yunnan provinces had released the Three-Year Action Plan for Cold Chain Logistics Development in Sichuan Province, the Chongqing Municipal Cold Chain Logistics Development Plan, and the Yunnan Province 14th Five-Year Plan for Cold Chain Logistics Development in 2018, 2019, and 2021, respectively [14].

2.2 Issues and Shortcomings in the Development of Agricultural Products Logistics in Western China

However, the cold chain logistics industry for agricultural products in Western China also faces certain challenges. These are primarily reflected in the following aspects: First, China’s agricultural cold chain logistics system suffers from weak infrastructure and regional imbalances, with cold storage resources concentrated mainly in eastern regions, while coverage in Western China is significantly insufficient. In 2021, Western China’s cold storage capacity stood at approximately 9.15 million tons (17.5% of the national total), and refrigerated trucks numbered 7460 units (17.1%) [14]. Cold storage facilities in China exhibit significant spatial imbalance and tend to be concentrated in key agricultural production and logistics hub regions [15]. This trend is particularly evident in areas such as Sichuan Province, Chongqing Municipality, and Shaanxi Province.

Second, the cold chain logistics sector in Western China suffers from supply chain disruptions between enterprises at various nodes due to a shortage of information technology and collaborative mechanisms. On one hand, the relatively insufficient network coverage and relatively underdeveloped operational and equipment technologies in Western China have led to Radio Frequency Identification (RFID), Global Positioning System (GPS), Electronic Data Interchange (EDI), and other IoT technologies facing challenges in practical implementation. This further exacerbates information silos within the cold chain system, where refrigerated trucks, cold storage facilities, and goods operate separately. Each segment of the cold chain logistics network functions independently. On the other hand, enterprises lack real-time monitoring of temperature and humidity, as well as the ability to optimize transport routes. This lack of real-time monitoring results in persistently high spoilage rates for fruits and vegetables. For instance, fresh produce from Xinjiang suffers spoilage rates as high as 20% to 30%, while the cold chain storage and transportation rate for fruits remains below 10% [16].

Moreover, third-party logistics (3PL) providers in Western China play a relatively minor role in cold chain transportation. For instance, Xinjiang has over 5000 legally registered logistics enterprises, yet specialized third-party logistics companies account for only 6% of the total [16]. At present, third-party cold chain logistics in Western China primarily involves freight forwarding, inventory management, and cargo loading and unloading operations. Development in this sector has been relatively slow, with scarce service offerings. Only a handful of 3PL companies can ensure accurate and stable temperature control throughout the entire refrigerated supply chain. 3PL enterprises in the region have yet to establish a networked cold chain node system, resulting in suboptimal cold chain service levels.

The fourth major issue is that standardization and marketization remain insufficient. For instance, the Sichuan–Tibet region has yet to establish a comprehensive local cold chain logistics standard system. Existing technical specifications remain relatively general and lack timely updates, which is consistent with the widely reported absence and lag of cold chain logistics standards in China [17]. Furthermore, the region currently operates primarily through wholesale markets, with diverse models including farm-to-supermarket partnerships and participation from agricultural product chain supermarkets. Logistics enterprises play a limited role in agricultural product sales models, and specialized, socialized logistics models have yet to be established. This situation has exacerbated the region's issues of low operational efficiency within the industry and persistently high circulation losses.

Against this backdrop, these structural deficiencies in cold chain logistics are particularly evident in the transportation and storage of meat products, which impose even stricter requirements on temperature control and supply

chain integrity. For meat products, the development challenges in economically underdeveloped regions of Western China stems from the fact that, despite abundant meat industry resources and a significant share of national meat production, there remains a lack of investment and inadequate infrastructure across all stages of the fresh meat supply chain. It severely constrains the growing demand for fresh meat among local consumers. Current research indicates that the quality changes of refrigerated meat products exhibit a pronounced coupled effect of time, variety, and origin [18].

To address the uneven development of agricultural cold chain logistics in Western China, greater emphasis should be placed on coordinated infrastructure investment, particularly in cold storage facilities and refrigerated transport networks in remote production areas, in order to reduce regional disparities and improve accessibility. At the same time, these physical improvements need to be complemented by stronger digital integration through IoT-based technologies such as RFID, GPS, and real-time monitoring platforms, which can enhance information sharing, route optimization, and supply chain collaboration.

In addition, the cold chain service capacity of this region can be substantially strengthened by fostering specialized third-party logistics providers and encouraging the formation of networked cold chain nodes, enabling more professional and standardized temperature-controlled services. Parallel to this, the establishment of updated regional technical standards and more market-oriented logistics models is essential to improve operational efficiency, reduce circulation losses, and move beyond reliance on traditional wholesale systems.

These challenges become particularly critical for meat products, which require stricter temperature control and quality assurance. Therefore, comprehensive upgrading across slaughtering, processing, refrigerated distribution, and safety supervision is necessary to minimize spoilage risks and better satisfy the rising demand for fresh meat in economically underdeveloped western regions.

2.3 Recommendations for the Development of Agricultural Products Logistics in Western China

It is expected that horizontal and vertical cold chain corridors will be established in the future. Specifically, horizontal corridors include the Longhai–Lanxin Railway (for fruit), the Yangtze River Golden Waterway (for citrus), and the Land–Sea New Channel in Western China (for vegetables). Vertical corridors can include the Baoji–Xi'an–Xikang Railway (meat) and Baoji–Chengdu–Chengdu–Kunming Railway (specialty fruits). Also, five national-level cold chain hubs can be established in Xi'an, Chongqing, Chengdu, Nanning, and Urumqi, featuring multi-temperature, multi-tiered intelligent cold storage clusters for transshipment.

Standardized protocols, unified scheduling, and consolidated billing will form multimodal transport products. These products combine rail cold chain trains, cross-border road freight, and air chilled cargo routes, while also increasing cold chain train frequencies on the Land-Sea New Channel in Western China. In addition, routes such as Chongqing–Beibu Gulf–Singapore, Chongqing–Pingxiang–Hanoi, and Chengdu–Alashankou–Europe can be launched in the future, thereby establishing a total of 15 international cold chain routes. This is expected to enable direct delivery of Western fruits, meats, and dairy products to Regional Comprehensive Economic Partnership (RCEP) countries and Middle Eastern markets.

Second, shared cloud-based cold storage facilities can be promoted in the region. The government should lead the development of the large-scale, networked, and standardized cold storage infrastructure to reduce agricultural product losses during distribution and stabilize market prices [19].

Third, the government should establish a dedicated fund to support enterprises in collaborating with major logistics providers to build overseas cold chain warehouses. It should further develop cold chain transportation routes via the China–Europe Railway Express to ensure stable agricultural product shipments. For cross-border agricultural e-commerce exports, the government should encourage businesses to first transport agricultural products via cold chain to overseas warehouses before centralized distribution through overseas platforms or offline channels. Such approach will reduce cross-border logistics costs and losses for fresh fruits [20].

Finally, a carbon footprint database for the western cold chain can be established to record temperature, energy consumption, and carbon emissions in real-time on the blockchain, generating carbon labels that serve as credentials for accessing premium markets in the EU and North America. A Western Region Cold Chain Green Industry Alliance should be formed to unify standards for green procurement, green finance, and green certification.

3. Current Status of Agricultural Products Logistics Technology Development

3.1 Logistics Technology for Meat Products

According to China's current standards, Chinese meat products are primarily categorized into three types: Hot fresh meat, chilled meat, and frozen meat. Hot fresh meat refers to carcasses that are sold directly after slaughter without any cooling treatment. Chilled meat, also known as fresh chilled meat, refers to raw meat that has undergone rapid cooling after slaughter, bringing its core temperature to between 0 °C and 4 °C usually within 24 hours, thereby removing acids from the meat and allowing it to mature [21]. Frozen meat refers to meat preserved through freezing and subsequent storage at low temperatures, where the extent of quality changes depends on the ice crystalline size

and distribution, which itself is governed by freezing rate and storage temperature and duration [22]. Fig. 3 outlines the main steps in the cold chain logistics process.

3.1.1 Cold Chain Logistics Technology for Frozen Meat

Frozen meat products, including pork and beef, are typically stored in sealed freezer cabinets [23]. In addition, phase-change refrigeration is commonly used in the cold chain logistics for frozen meat transportation. This method involves placing phase-change materials within refrigerated truck bodies or insulated packaging. These materials store cold energy through phase transitions, utilizing latent heat. The stored cold energy is then transferred to maintain the storage temperature of perishable agricultural products inside the vehicle [24]. Experiments conducted by researchers have demonstrated that increasing the mass of the phase change material (PCM) significantly extends the cold storage duration. The experimental results showed that when the PCM mass was increased from 100 kg to 200 kg and further to 300 kg, the proportion of time that the air temperature remained below 10 °C increased from 66.3% to 92.1% and 94.7%, respectively, under natural convection conditions [25].

Regarding the application of relevant technologies for frozen meat refrigeration systems, integrating shell-and-tube PCM heat exchangers directly into the vapor-compression circuit has been demonstrated to enhance system performance. This configuration utilizes the latent heat of PCMs to increase sub-cooling and stabilize superheat, which in experimental studies improved the system's coefficient of performance by approximately 4%–8% and reduced temperature fluctuations critical for maintaining frozen meat quality [26].

Natural active packaging films are relatively common in frozen meat packaging. They primarily use polysaccharides, proteins, lipids, and other materials as substrates, with the addition of plasticizers and natural active substances. Prepared through processes such as casting and coating, these films can reduce dry loss, inhibit oxidation, and delay quality deterioration. Santos and others added Acerola cherry residue extract to natural gelatin active packaging films and found that when the additive concentration was 4%, it could maintain the film's opacity and reduce the formation of formaldehyde and total carbonyl compounds in frozen beef patties by 23.58% and 60.14%, respectively [27].

Furthermore, GPS and General Packet Radio Service (GPRS) technologies have been widely used in cold chain logistics monitoring systems. For example, a multi-layer monitoring architecture integrating vehicle-mounted terminals, communication modules, and remote monitoring platforms has been developed to enable real-time transmission of location and temperature data, thereby supporting transportation tracking, condition monitoring, and traceability functions [28].

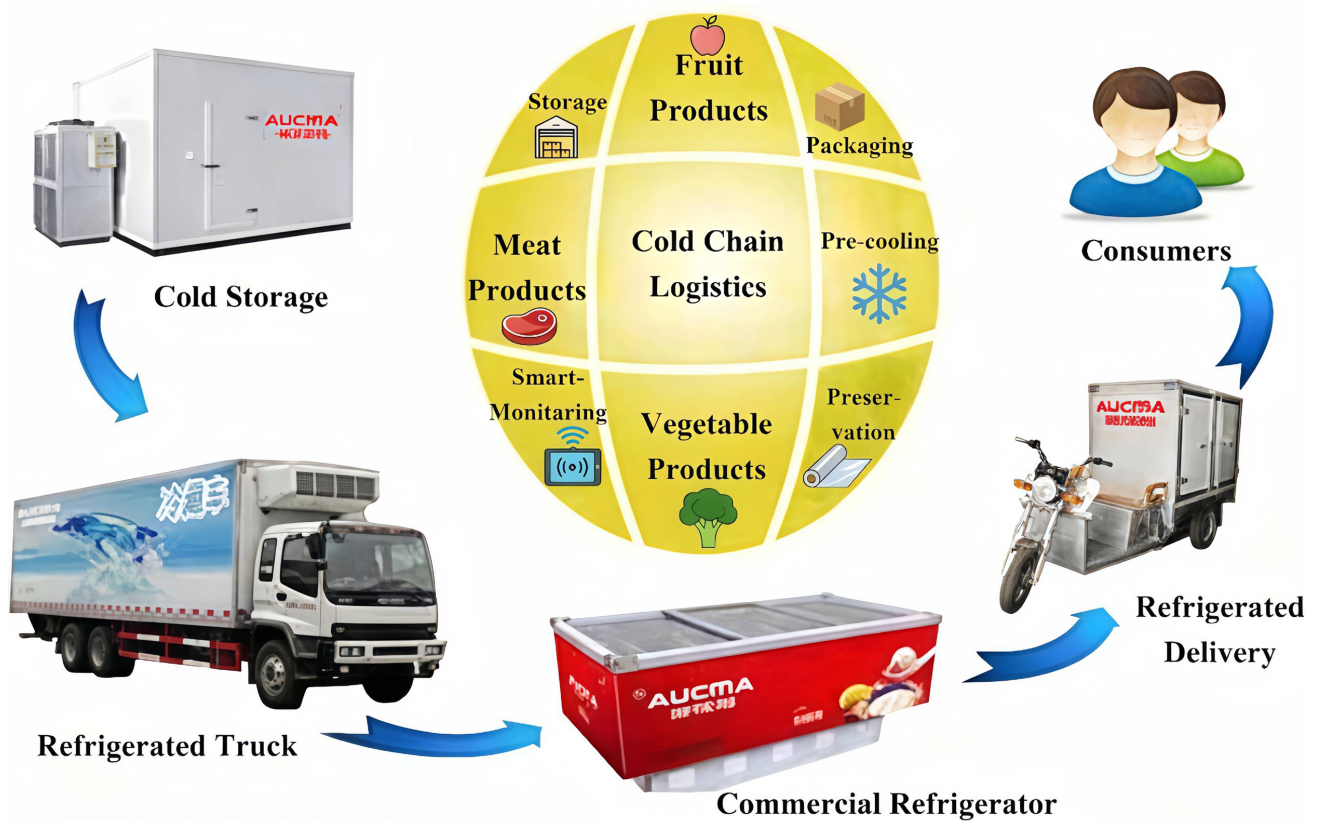


Fig. 3. Conceptual framework of agricultural cold chain logistics operations.

3.1.2 Cold Chain Logistics Technology for Chilled Meat

The shelf life of chilled fresh meat is generally around one week. During logistics transportation, temperatures are typically maintained between 0 °C and 4 °C using refrigerated trucks for cold chain delivery. The temperature inside the refrigerated cargo compartment is kept at 2 °C to prevent deterioration in meat texture and ensure effective preservation. Even under low-temperature conditions, cold chain products experience a gradual decline in freshness over extended transit times. Contributing factors include internal and external vehicle temperatures, transport duration, unloading time, and spoilage rates [29].

To address challenges in temperature sensing and real-time monitoring during transportation, Wu and Zhao [28] developed an IoT cold chain system with RFID, sensors and GPRS modules. Tests showed average transport temperatures of 2.0 °C ± 1.3 to 4.6 °C ± 1.1, reaching 4 °C within 0.5 to 11.9 hours, and final delivery temperatures of 1.0 °C to 3.4 °C. As a result, real-time monitoring can capture fluctuations and identify spatial variations, thereby enabling timely intervention and improving management precision [28].

To control bacterial growth during transport, irradiation technology can be employed for sterilizing products with radiation [30]. Research by Badr [31] indicates that exposing rabbit meat samples to a γ -ray irradiation dose of 3000 Gy effectively controls foodborne pathogens, with the

initial population of *Enterococcus faecalis*, for example, reduced by 96.3%. This extends the refrigerated shelf life to 21 days.

3.1.3 Cold Chain Logistics Technology for Fresh Meat

Since temperature and humidity are critical to meat quality and safety, hot fresh meat is typically stored in horizontal refrigerated cabinets where operating temperatures are carefully maintained within chilled conditions, typically around -2 °C to 2 °C [32]. Meanwhile, relevant IoT technologies can be utilized in the cold chain logistics of fresh meat agricultural products to monitor environmental and quality factors. Blockchain-enabled temperature and humidity monitors can be used for agricultural product traceability, enabling real-time on-chain registration and tamper-proof storage of cross-linkage flow information for meat products. This enables transparent traceability of temperature conditions throughout the cold chain. Additionally, integrated sensors can be used to simultaneously upload temperature, humidity, and environmental data to a blockchain-based information system, enabling dynamic monitoring and early warning [33].

RFID refers to a technology that utilizes radio waves to achieve non-contact automatic identification of target objects and remote data transmission [34]. This technology enables comprehensive information recording and traceability throughout the meat cold chain, while simultane-

ously monitoring multiple packaging targets and product information [35]. These temperature and humidity sensors are typically inexpensive, compact, and suitable for various packaging applications. Their operating principle is solely influenced by temperature, making them immune to external factors such as light and humidity. Additionally, blockchain smart contracts—specifically those based on Hyperledger Fabric technology and written in the GO language—enable real-time monitoring of temperature and humidity data. Exceeding thresholds triggers alerts and activates emergency protocols, ensuring timely risk response. This real-time monitoring provides early warnings to ensure the integrity and precise control of meat product cold chain logistics, enabling timely responses to changes in internal environmental conditions. This helps ensure appropriate temperature and humidity throughout the meat cold chain, preventing spoilage caused by temperature and humidity disruptions [36].

Active Packaging (AP), Intelligent Packaging (IP), and Green Packaging (GP) are the three core packaging solutions in meat cold chain transportation, each of them focuses on many different aspects but works synergistically toward a common goal. AP incorporates active substances like antimicrobial agents and antioxidants, or absorbs and releases specific components to inhibit microbial growth and lipid/protein oxidation, prevent cross-contamination, and extend meat shelf life; IP utilizes devices like Near Field Communication (NFC) tags and temperature-humidity indicators to monitor the internal environment and meat quality in real-time, record traceability information, and provide feedback on quality changes, supporting supply chain management and consumer decision-making; GP utilizes natural, renewable, biodegradable, or edible eco-friendly materials infused with natural active ingredients like green extracts. This approach ensures meat safety and health while reducing environmental impact, minimizing food waste, and lowering production costs. The development trends of these three approaches exhibit convergence, intelligence, and greening characteristics. Examples include nanomaterial applications, synergistic effects of multiple active ingredients, and real-time monitoring of remaining shelf life. The ultimate goal is to achieve integrated composite packaging that combines the advantages of all three, leveraging multidisciplinary technologies such as meat science and microbiology to create safer, more efficient, and environmentally friendly meat cold chain logistics solutions [37].

Specific schematic diagrams of the three packaging types mentioned above are shown in Fig. 4 (Ref. [37]). A review of existing research indicates that cold storage, electron beam irradiation, and active packaging are highly effective in preserving fresh meat. However, the appropriate applications for these technologies vary significantly. Cold storage requires high precision and is costly, making it more suitable for high-value-added meats; irradiation provides

thorough sterilization but involves high equipment costs; and active packaging is environmentally friendly and safe but lacks long-term effectiveness. Most existing studies focus on individual technologies and lack comparative validation of multi-technology synergies adapted to the high-altitude environment of Western China.

3.2 Logistics Technology for Vegetable Products

Researchers have developed pressure differential pre-cooling systems, which include pressure differential pre-cooling chambers for fruits and vegetables, as well as split-type, integrated, and mobile pre-cooling units. These systems also incorporate immersion-type cold-water pre-cooling equipment to achieve rapid temperature reduction and energy efficiency. Additionally, researchers introduced portable cold storage insulation equipment using vacuum insulation panels and polyurethane composite materials. The use of phase change latent heat materials enhances cold storage efficiency at 0 °C [38].

3.2.1 Primary Pre-cooling Methods for Vegetable Products

Current pre-cooling methods for vegetable agricultural products include air pre-cooling, water pre-cooling, and vacuum pre-cooling. Air pre-cooling primarily encompasses forced-air pre-cooling, pressure differential pre-cooling, and wet pre-cooling, while water pre-cooling mainly includes cold water pre-cooling and other pre-cooling methods.

Forced-air pre-cooling refers to a method where fruits and vegetables are placed in a low-temperature airflow environment. Cold air flows over the surface of the produce, utilizing convective heat transfer to rapidly remove internal heat and achieve a swift temperature reduction [39]. Alibas I and Koksal N [40] conducted forced-air pre-cooling by exposing cauliflower to a low-temperature airflow. Under an airflow velocity of 1 m/s, cauliflower heads with an initial temperature of 23 °C could be cooled to the target temperature of 1 °C within 184 minutes. Their study measured a cooling rate of 0.025 for the forced-air pre-cooling system. By circulating cold air over the surface of the cauliflower, heat transfer via convection was achieved, facilitating the transfer of heat from the outer surface to the inner surface [40].

Due to its significantly faster cooling rate and more uniform temperature distribution compared to traditional forced-ventilation pre-cooling, differential pressure pre-cooling is suitable for pre-cooling various vegetables. Xu Qinglian et al. [41] found that pressure differential pre-cooling enables cabbage to maintain low temperatures for extended periods while suppressing respiratory metabolism and enzyme activity. This effectively inhibits the growth of total bacterial counts and coliform bacteria, thereby delaying the onset of browning throughout the entire cold chain [41].

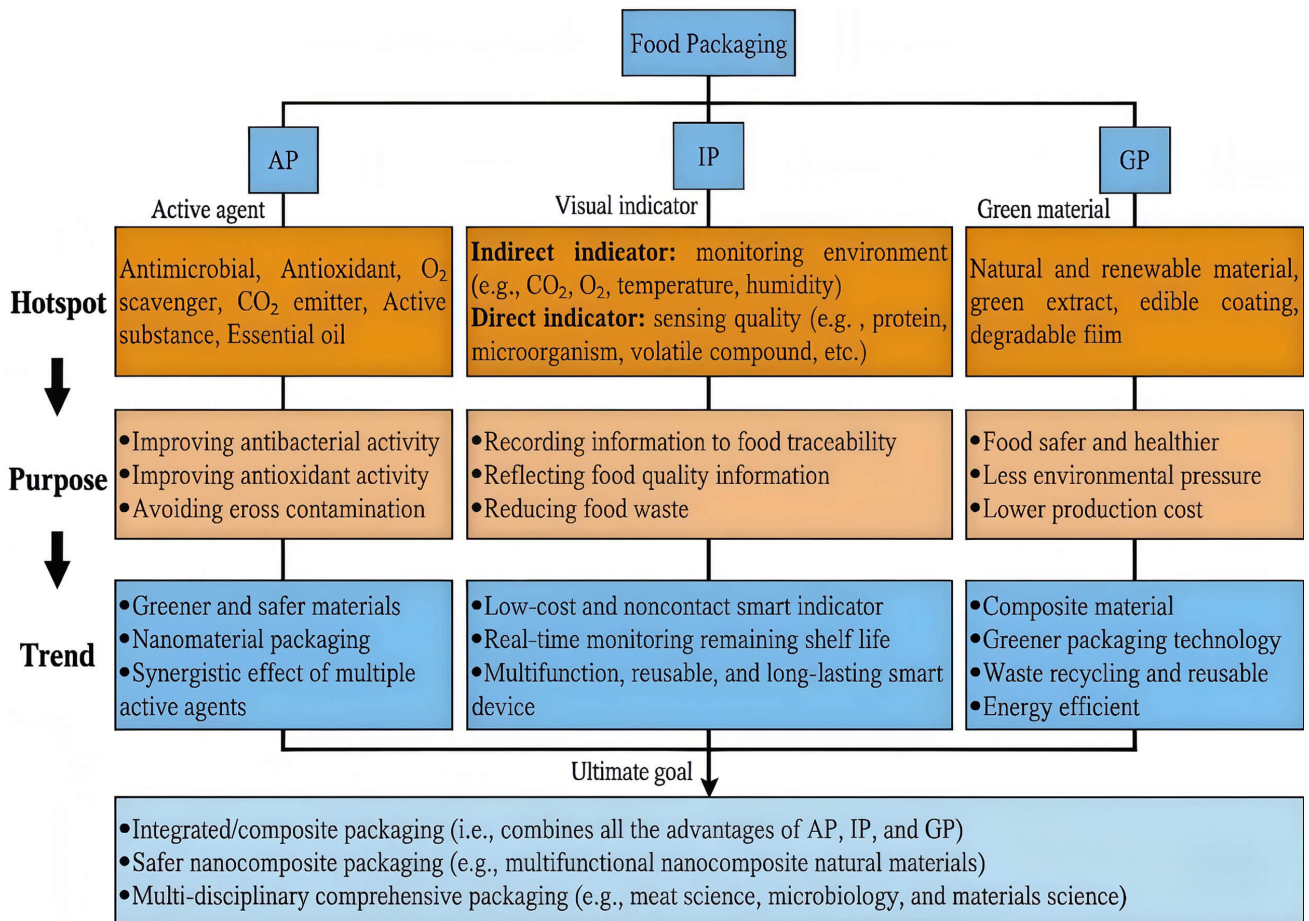


Fig. 4. Classification of main intelligent packaging for fresh meat [37]. AP, Active Packaging; IP, Intelligent Packaging; GP, Green Packaging.

The mechanism of wet-cold pre-cooling relies on direct contact between airflow and cooling water within a direct-contact heat exchanger, enabling simultaneous heat and mass transfer. This produces low-temperature gas with high relative humidity, which is then delivered to stored produce via forced ventilation. This achieves rapid and efficient heat extraction, significantly lowering product temperature in a short time [42]. Ren Xueming et al. [43] developed a wet-cooling precooling system and experimentally compared its performance with that of a conventional mechanical cold storage facility for strawberry precooling. The results indicated that, relative to conventional mechanical cold storage, the wet-cooling system exhibited smaller fluctuations in both temperature and humidity, achieved a faster precooling rate, and was therefore more suitable for strawberry precooling [43]. Su Mingqiang et al. [44] investigated the effects of different packing materials on the pre-cooling performance of king oyster mushrooms in a wet-cooling pre-cooling warehouse using ice slurry as the secondary refrigerant. They found that the use of ceramic and paper wet curtains resulted in temperature fluctuations under 0.28%. Regarding pre-cooling efficiency, wire mesh corrugated packing achieved the fastest cooling rate, re-

quiring only 70.2 minutes to reduce the average core temperature from approximately 23.0 °C to 2.0 °C. The lowest weight loss rate was also only 2.65%. Conducted under optimized conditions—6% ice content in the ice slurry, 1.5 m/s airflow velocity, and 125 L/h ice slurry flow rate—this study validated that the ice slurry wet-cooling heat exchanger, when paired with high-efficiency packing, can achieve a low-temperature, high-humidity pre-cooling process with a final temperature of -1 °C and relative humidity exceeding 90% [44].

Cold water pre-cooling is a form of precooling in which the product is sprayed with or immersed in an agitated bath of chilled water [45]. Gillies S and Toivonen P [46] compared the effects of cold-water pre-cooling and two other pre-cooling methods on broccoli storage quality, finding cold water pre-cooling to be the fastest. Additionally, cauliflower packaged in porous film exhibited a weight loss rate of only 2.1% after cold water pre-cooling, lower than both cold storage pre-cooling and ice pre-cooling. Furthermore, cold water pre-cooling reduces the vapor pressure deficit (VPD) between the product and surrounding air, which helps minimize water loss during the initial storage period of broccoli [46]. Cold water pre-cooling uti-

lizes a chilled water circulation system as its core equipment, requiring frequent flushing during operation. This pre-cooling method is currently suitable for rapidly lowering the temperature of fruits, vegetables, and root crops, but does not apply to leafy vegetables [47].

Vacuum pre-cooling is a pre-cooling technique that rapidly lowers the surface temperature of vegetables by utilizing atmospheric pressure to evaporate moisture and absorb heat [48]. Liu JY et al. [49] evaluated the effects of vacuum pre-cooling combined with modified atmosphere packaging (MAP) versus vacuum pre-cooling alone on the shelf life of cabbage. The result showed that vacuum pre-cooling could reduce the temperature to 7 °C within 30 minutes. Furthermore, after 12 weeks of storage, the yellowing index of the vacuum pre-cooling plus MAP treatment group was significantly lower than that of the control group. At the same time, the use of modified atmosphere packaging effectively reduced weight loss in cabbage during storage. Therefore, the combination of vacuum pre-cooling and modified atmosphere packaging can be effectively applied to the postharvest preservation of cabbage [49]. He S and Li Y's research [50] revealed that lettuce requires only 32 minutes to pre-cool from 18 °C to 1 °C, with a weight loss of just 2.97%. Additionally, Tian Ding et al. [51] conducted a comparative experiment to evaluate the effects of vacuum pre-cooling and other pre-cooling methods on the shelf life of broccoli. The results showed that vacuum cooling could reduce the temperature to 5.5 °C within 30 minutes, which was significantly lower than that of the control group. After one month of storage, the reducing sugar content in the vacuum-cooled group was 27.88 mg/100 g, significantly higher than that of the other control groups. Furthermore, the application of water spraying reduced weight loss in the broccoli to only 1.47%, far lower than the 15.38% observed in the control group, without compromising quality. Therefore, the researchers concluded that the combination of vacuum cooling and water spraying can be effectively applied for the postharvest preservation of broccoli [51].

3.2.2 Primary Technologies for Vegetable Cold Chain Storage

After reviewing the primary pre-cooling technologies for vegetable agricultural products, it is essential to integrate appropriate cold chain low-temperature storage techniques to effectively maintain vegetable quality and extend shelf-life post-pre-cooling. This stage constitutes a critical component of the cold chain logistics system, as it directly impacts product quality preservation and loss control during subsequent distribution and sales. Applying this technology enables vegetables to maintain high quality throughout subsequent transportation phases. Contemporary researches regard low-temperature storage as one of the primary methods for preserving leafy vegetables [52]. This section will focus on describing the common technical methods currently employed in vegetable cold chain storage.

3.2.2.1 Low-Temperature Storage. The primary types of cold storage facilities used for low-temperature storage of vegetable agricultural products include high-temperature cold storage (with internal temperatures of 5 °C–15 °C) and medium-temperature cold storage (with internal temperatures of –5 °C–5 °C). Current research indicates that when the cold storage's air distribution system is arranged along the length of the storage chamber and employs a side-central airflow configuration, it helps improve the temperature uniformity of vegetables, thereby effectively enhancing the storage quality of the entire batch of fruits and vegetables [53]. Ulrike Praeger et al. [54] investigated the effects of stacking arrangements and fan placement on airflow distribution in industrial apple storage facilities. Their results indicated that placing fans above vertical gaps, combined with a side-to-center airflow configuration, was more effective in ventilating the crates than placing them above the rows of crates. Furthermore, compared to layouts with no gaps or narrow wall-to-wall gaps (about 10 cm), a stacking layout featuring a central vertical gap between the rows of crates significantly improves airflow uniformity [54].

3.2.2.2 Controlled Atmosphere Storage. Controlled atmosphere storage is a preservation method that operates under low-temperature conditions. By regulating the concentrations of gases such as carbon dioxide and oxygen, along with temperature and humidity within the storage space, it creates an environment conducive to suppressing respiration, delaying aging, and maintaining the sensory and nutritional qualities of vegetables [55]. This technology can be primarily categorized into two types: Modified Atmosphere Storage (MA) for spontaneous gas regulation and Controlled Atmosphere Storage (CA) for mechanical gas regulation. The former primarily utilizes low-permeability plastic films to adjust the oxygen and carbon dioxide concentrations within the packaging in a single step, thereby suppressing vegetable respiration. The latter employs mechanical devices within low-temperature controlled atmosphere storage facilities to continuously regulate gas composition, preventing cold damage [56,57]. Wang Xiaoyan et al. [58] found that under controlled atmosphere storage conditions of 5% O₂ and 8% CO₂, edamame beans retained chlorophyll a and chlorophyll b at levels of 40.32 µg/g and 20.37 µg/g, respectively, by the 20th day of storage, which were significantly higher than those in the control group. This demonstrates that the technology effectively delays chlorophyll degradation by precisely regulating the gas environment, thereby preserving the quality and color of vegetables [58].

3.2.2.3 Reduced-Pressure Storage. Reduced-pressure storage is a postharvest technique for vegetables that lowers the total air pressure by extracting air from the storage chamber, thereby creating a partial vacuum environment [59]. Sang Yu et al. [60] conducted a study by setting

up three control groups under atmospheric pressure, 50 kPa, and 30 kPa, storing vegetables at $(4 \pm 1) ^\circ\text{C}$, and measuring indicators such as vitamin content. They found that under 30 kPa pressure conditions, the vitamin C content maintained 43.3% of its initial value, while other indicators also outperformed corresponding data under other pressure conditions. This demonstrates that 30 kPa vacuum treatment enhances the freshness retention of vegetables [60]. Shen Jiang et al. [61] designed a vacuum-precooled reduced-pressure storage experiment. Through continuous vacuum pumping and humidification system air intake, the storage chamber pressure was maintained at approximately (1 ± 0.04) kPa, ultimately achieving a water loss rate of only 3.34% for Chinese cabbage [61].

3.2.2.4 Ice-Temperature Storage. Ice-temperature storage refers to preserving vegetables at temperatures below $0 ^\circ\text{C}$ and freezing temperature. This technique extends storage duration while significantly suppressing the vegetables' own metabolic activity and the proliferation of spoilage microorganisms [62]. Lin Benfang et al. [63] found that at $-0.7 ^\circ\text{C}$ cold storage conditions, cold storage could respectively increase the activity of broccoli peroxidase (POD), superoxide dismutase (SOD), and catalase (CAT) by approximately 11.7%, 110.7%, and 28.1%, respectively, while simultaneously reducing polyphenol oxidase (PPO) activity by approximately 15.0%, thereby delaying broccoli senescence [63].

Ice-temperature storage is now widely used for storing agricultural products such as jujubes [64]. However, despite these advantages, the application of this technology is constrained by the narrow ice-temperature range and the need for precise temperature control. For instance, green beans exhibit superior physiological and commercial quality under ice-temperature storage conditions compared to storage at $8 ^\circ\text{C}$ or $25 ^\circ\text{C}$. Furthermore, since the optimal ice-temperature range varies among different vegetables, and pallet loading and unloading operations can disrupt storage temperature stability, establishing ice-temperature storage facilities demands high technical requirements and significant investment [65].

3.2.3 Application of RFID and Other Major IoT Technologies in Vegetable Cold Chain Logistics

RFID technology is widely applied in the cold chain transportation of agricultural products. It encompasses three core components: transponders (tags), readers, and radio frequency antennas. The operational mechanism of this technology involves three critical stages: information reading, decoding, and information processing within the application software system [66].

Building on this technical foundation, RFID can be implemented throughout the entire cold chain transportation process for vegetable agricultural products. It simultaneously covers quality supervision and traceability

queries across all stages, achieving full traceability and standardized oversight of fruit and vegetable cold chain logistics through comprehensive information collection, coding identification, and data management [67]. Furthermore, RFID can be integrated with NFC technology to enhance this capability by enabling more refined environmental monitoring. Specifically, it allows for real-time tracking of critical ambient parameters, such as temperature, humidity, and light, which are essential for maintaining the quality and safety of fresh produce throughout the supply chain [68].

Additionally, RFID technology can be integrated with positioning systems such as GPS to collect information on the location and speed of transport vehicles. It then transmits data gathered during transportation—including license plate numbers and cargo details—to the monitoring center via wireless network communication. Simultaneously, the information collected during transport is loaded onto the vehicle's RFID electronic tag [69]. Also, electronic tags are installed on shelves to pre-plan vegetable storage locations. During unloading, readers quickly verify vegetable details. When shelving, scanning tags transmits data to the Warehouse Management System (WMS), automatically updating vegetable inventory. During warehouse picking, scanning errors immediately trigger alarms. The final sorting stage employs scanners to ensure accurate vegetable allocation and prevent omissions.

On the other hand, the type of transport vehicle should be selected based on the duration of the journey. According to QC/T449 standards cited by Liang Huafeng [70], insulated vehicles with temperatures under 18 degrees Celsius are recommended for trips under 10 hours. For journeys exceeding 10 hours or when ambient temperatures exceed $30 ^\circ\text{C}$, refrigerated vehicles maintaining temperatures under 12 degrees Celsius must be used [70]. A comparison of various pre-cooling and storage technologies reveals that differential pressure pre-cooling offers the highest efficiency but imposes stringent packaging requirements. Vacuum pre-cooling is best suited for leafy vegetables but results in slightly higher losses, and modified atmosphere storage provides a longer shelf life but requires significant investment. In the mountainous regions of Western China, where road networks and electricity supply are limited, high-efficiency, low-cost wet pre-cooling and simple ice-cooled storage facilities hold greater potential for widespread adoption. However, existing research on the comparative suitability of these methods remains limited.

3.3 Logistics Technology for Fruit Products

3.3.1 Cold Storage and Differential Pressure Control Technology

Cold storage facilities remain the critical equipment for the cold chain of fruit and vegetable agricultural products, with temperatures ranging from 5 to $15 ^\circ\text{C}$ (high-temperature) and -5 to $5 ^\circ\text{C}$ (medium-temperature) cold

storage facilities exhibiting the highest adoption rates in fruit pre-cooling and low-temperature storage at production sites. Wang Xuan et al. [71] employed pressure differential processing technology to create an inlet-to-return air pressure gradient within sealed cold boxes, forcing cold air to permeate through layers of spherical and cylindrical fruit. This technique achieves 2–6 times higher pre-cooling efficiency than conventional cold storage, significantly accelerating temperature reduction, improving cooling uniformity, and minimizing moisture evaporation [71]. Wang Junyan et al. [72] investigated the differences between vertical and horizontal placement of cucumbers under pressure differential treatment through simulation and experimental studies. They found that vertical placement resulted in faster cooling and better uniformity, with the slowest cooling time being 150 minutes compared to 180 minutes for horizontal placement. Although the weight loss rate was slightly higher, the overall cooling effect was superior. Vertical placement is recommended for cylindrical fruits and vegetables [72]. Wu et al. [73] found that while staggered stacking offers mechanical stability, it obstructs vertical ventilation and reduces cooling uniformity. Regular stacking maintains aligned airflow pathways, achieving faster and more uniform pallet cooling. Considering cooling efficiency and economic feasibility, regular stacking is optimal for commercial cold chain operations [73]. Therefore, the method of pressure differential treatment varies depending on the shape of the fruit.

3.3.2 Thermal Treatment Preservation Technology

Thermal treatment for freshness preservation involves treating fruits post-harvest with heat sources above their ripening temperatures. This process kills or inactivates pathogenic bacteria through high temperatures while regulating fruit metabolism, thereby reducing spoilage [74]. Currently, this technology is primarily achieved through methods such as hot air and hot water immersion. Bianca Almada Ferreira Gomes et al. [75] treated pomegranates with 50 °C hot water for 10 to 30 minutes, finding that this effectively maintained the quality of minimally processed guavas while minimizing microbial growth. Ma et al. [76] found that apples yielded optimal texture when stored for 24 hours before slicing, followed by a 10-minute pre-treatment in 50 °C water. This thermal treatment was shown to inhibit the increase in total phenolic content, thereby suppressing enzymatic browning and enhancing the resistance of fresh-cut apples to discoloration. The method also provided effective color retention, preserving the apples' vibrant appearance [76]. Wei et al. [77] discovered that treating cherry tomatoes with hot air at 38 °C for 12 hours significantly enhances disease resistance by activating the phenylpropanoid metabolic pathway, reducing the incidence of *Fusarium* and gray mold *Botrytis* as well as the diameter of lesions [77].

3.3.3 Smart Monitoring Sterilization Technology

Xinqing Xiao et al. [78] constructed a simple wireless sensor network using a combination of wireless sensors containing CC2538 and SHT10 sensors and a GPRS coordinator, enabling multi-level monitoring of grape refrigerated truck compartments. This wireless sensor network comprised 27 sensor nodes and one network coordinator node, enabling continuous operation within refrigerated truck compartments for 15 days [78]. The specific layout blueprint is shown in Fig. 5 (Ref. [78]).

Additionally, Researchers found that in a smart specimen transport system incorporating RFID and Narrowband Internet of Things (NB-IoT) technologies, passive RFID tags enable multi-tag reading and writing under non-line-of-sight conditions. Made of plastic, these tags are waterproof and heat-resistant, and can be easily attached to specimen tubes that require sterilization. In addition, the NB-IoT devices installed in the sample transport boxes can monitor temperature and humidity levels in real time during transit, while GPS location data is reported to a cloud platform to estimate delivery times [79]. Another representative study found that under controlled cold-chain conditions (−1–3 °C for 16.7–18 days), a sensor-based digital twin system achieves at least 99.9968% pest mortality, ensuring highly reliable sterilization performance. This was reflected in a significant increase in the mortality rate of Mediterranean fruit flies in the study, with 41 out of 43 shipments achieving a 100% pest mortality rate, and all shipments arriving at the retail stage completely free of pest infestation [80]. A review of the literature on fruit cold chain logistics indicates that differential pressure pre-cooling, heat treatment, and smart sensing are the mainstream solutions. However, the suitability varies significantly across different fruit types: tropical fruits are better suited for heat treatment to inhibit bacterial growth, while temperate berries rely more heavily on precise temperature control and wireless monitoring. There is still a lack of systematic comparative conclusions regarding the impact of the low-temperature, low-oxygen environment in high-altitude production areas in Western China on technical parameters.

4. Optimization of Cold Chain Logistics Distribution Routes

The cold chain logistics delivery route optimization problem also falls under the Vehicle Routing Problem (VRP), which is a non-deterministic polynomial-time hard (NP-hard) problem. It can primarily be divided into the following subproblems, as shown in Table 1:

The VRP can be systematically categorized across multiple dimensions. First, based on the number of distribution centers, VRP problems can be classified into Multi-Depot Vehicle Routing Problem (MDVRP) and the basic original VRP problem, which involves only a single distribution center. Second, incorporating time window constraints, it encompasses no time window, soft and hard time

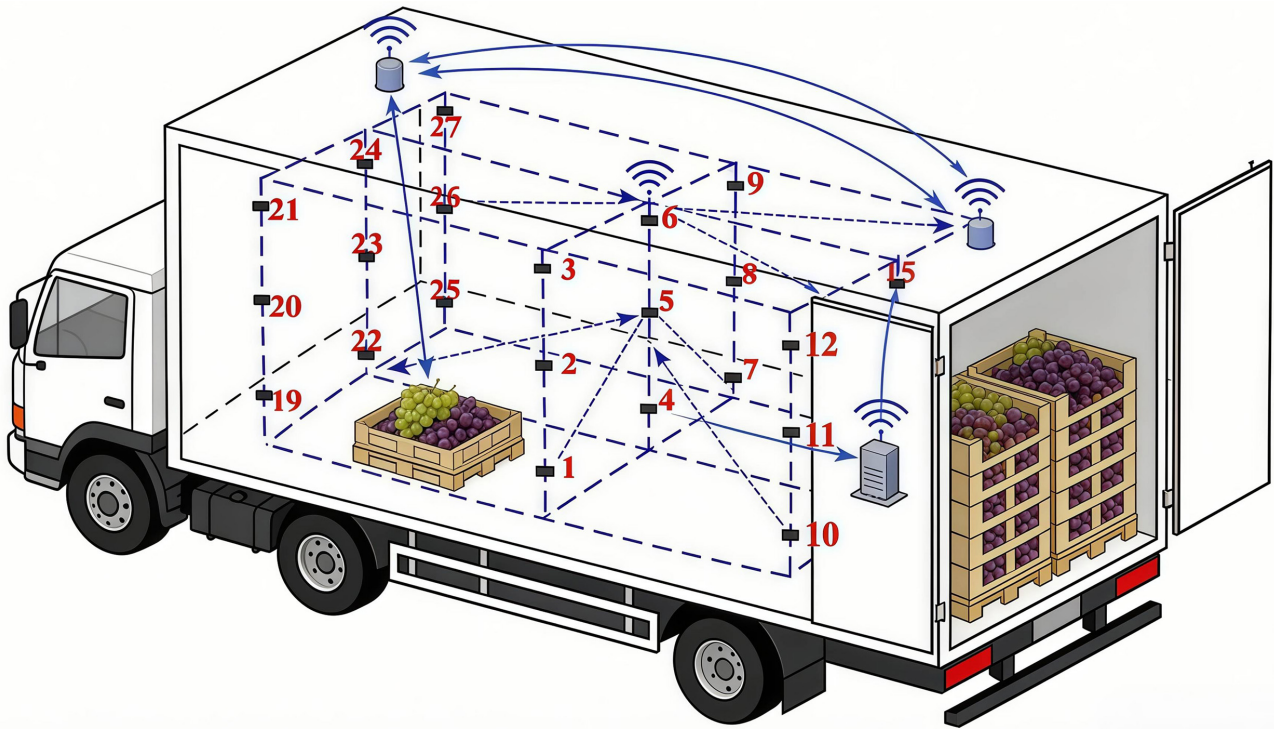


Fig. 5. Schematic diagram of wireless sensor monitoring in grape refrigerated trucks [78]. Each number here represents a sensor in the wireless sensor network (WSN) system installed in the grape refrigerated trucks. These sensors continuously monitor temperature and humidity parameters at various locations within the cargo compartment during the cold-chain transportation of fresh grapes. Data is fused at the node level to eliminate redundancy and errors, and the fused data is then transmitted remotely to the control center via the network coordinator. This enables transparent monitoring and traceability of temperature and humidity conditions throughout the entire cold-chain process, thereby ensuring transportation quality and food safety.

Table 1. Overview of VRP problem classification.

Basis for classification	Specific categories
Number of distribution centers	Vehicle Routing Problem (VRP)/Multi-Depot Vehicle Routing Problem (MDVRP)
Time-window constraint	No Time Window/Soft Time Window/Hard Time Window/Fuzzy Time Window
Vehicle type	Single-Vehicle Model/Multiple-Vehicle Model
Task type	Delivery Only/Pickup Only/Vehicle Routing Problem with Simultaneous Pickup and Delivery (VRPSPD)
Load condition	Fully Loaded/Not Fully Loaded
Divisibility of demand	Capacitated Vehicle Routing Problem (CVRP)/Split Delivery Vehicle Routing Problem (SDVRP)
Optimization goal	Single Task/Multi Task (Pareto)
Circuit mode	Closed VRP/Open VRP
Network dynamics	Static VRP/Dynamic VRP
Emerging expansion	Green VRP/Stochastic VRP/Cold Chain VRP/Crowd-sourced VRP/VRP-D

VRP, Vehicle Routing Problem.

windows, and fuzzy time windows, reflecting varying service timeliness requirements. Simultaneously, classification by vehicle type distinguishes single-vehicle and multi-vehicle scenarios, highlighting the impact of heterogeneous transport capacity on route planning. Additionally, task-based distinctions include delivery and pickup only, and simultaneous delivery-pickup (VRPSPD) modes, defining core operational differences in logistics scenarios. Building upon this foundation, the VRP problem can be further refined through factors such as load status, demand divisi-

bility, optimization objectives, loop patterns, network dynamics, and emerging extensions, including green VRP, stochastic VRP, and cold chain VRP.

In recent years, scholars around the world have primarily employed metaheuristic algorithms and hybrid algorithms, supplemented by simulation experiments, to optimize cold chain logistics distribution routes. Yi-hula Chen [81] utilized a cloud-based coarse-grained parallel genetic algorithm and found that it significantly reduces computation time while achieving near real-time route planning.

The improved ant colony algorithm achieves shorter total travel distances after incorporating constraints for transportation time, cold chain temperature maintenance, and road capacity, outperforming traditional ant colony and chaotic algorithms [82]. An advanced multi-objective ant colony algorithm can simultaneously consider cost, carbon emissions, and customer satisfaction [83].

Mei-xian Song et al. [84] employed an improved artificial fish swarm (IAFS) algorithm, combined with a specialized two-dimensional vector encoding scheme and a right-shift heuristic strategy, to efficiently solve a model for minimizing the total cost of cold-chain logistics delivery while accounting for time windows and energy consumption. The algorithm successfully planned optimal delivery routes, achieving better results in 41 out of 55 test instances [84]. Additionally, researchers combined the Christofides-Whitlock (C-W) algorithm with enhanced tabu search to solve large-scale vehicle routing problems with time window constraints, significantly improving computational efficiency [85]. To address the robustness requirements for road cascade failures, researchers combined Dijkstra search with genetic algorithms to construct a path model capable of dynamic detours [86].

Under the carbon neutrality framework, incorporating carbon emission penalties or carbon tax constraints into models can reduce carbon footprint while ensuring timeliness. Fine-grained Bacterial Foraging Optimization (BFO) and its improved variant (IBFO) demonstrate faster convergence and superior global search capabilities in low-carbon VRP scenarios [87]. For temperature-sensitive cold chain products, researchers developed a comprehensive cost function incorporating refrigeration costs, transportation costs, and penalty costs. By enhancing the ant colony optimization algorithm, they achieved approximately 16.6% reduction in total costs and decreased environmental pollution [88].

In multi-center collaborative delivery scenarios, a three-dimensional collaborative delivery model based on product type, spatial distance, and delivery time—combined with mathematical programming and simulation—significantly improves loading rates and reduces transportation costs [89]. Additionally, researchers have incorporated cargo damage, energy and carbon emission costs, along with time- and quality-based customer satisfaction constraints into multi-vehicle low-carbon VRP models, achieving reduced overall carbon footprint while maintaining service levels [90]. Finally, the introduction of an IoT real-time monitoring system enables the collection of critical parameters such as temperature, humidity, and location in real-time. These data are utilized for dynamic path adjustments, enhancing the system's robustness and traceability [91].

Wang Yan et al. [92] studied frozen beef and developed an improved Non-Dominated Sorting Genetic Algorithm II (NSGA-II) algorithm with adaptive crossover and

mutation probabilities to optimize cold chain multimodal transport routes. By dynamically adjusting algorithm parameters, effectively avoiding premature convergence issues in traditional algorithms, the approach balances cost and timeliness under uncertain transit times. This reduces frozen beef transportation costs, enhances time efficiency ratios, and optimizes cold chain distribution routes [92].

Wang Yong et al. [93] selected specific fruits, including cherries and grapes, based on the categories of fresh agricultural products and the temperature control requirements during transportation. Considering the dynamic nature of customer demand for fresh goods and delivery temperature specifications, they employed a Gaussian mixture clustering-based (GMC) ant colony optimization algorithm to solve the problem of optimizing delivery routes for fresh produce while constructing an integer programming model to minimize total costs. Simultaneously, they constructed a total cost minimization integer programming model, achieving approximately 10% cost reduction [93]. A comparison of various algorithms reveals that the improved ant colony optimization algorithm and the hybrid genetic algorithm perform better overall in terms of total cost and timeliness. The particle swarm optimization algorithm converges quickly but is prone to getting stuck in local optima; and the C-W algorithm is suitable for small-scale scenarios. There has been limited research on dynamic route optimization for Western China characterized by multiple hubs, long transport distances, and low-temperature environments, and comparisons of algorithm robustness remain insufficient.

5. Conclusions

This paper systematically reviews relevant research in the field of agricultural cold chain logistics in Western China based on a technology-product-region framework. The study indicates that various cold chain technologies, such as pre-cooling and cold storage, are not applied in isolation. Instead, they form a synergistic support system centered on the temperature control requirements of three major agricultural product categories: meat, vegetables, and fruits. This framework must be adapted to the distinct resource advantages, topographical conditions, and logistics corridor differences of the Northwest and Southwest China. Fig. 6 illustrates the internal relationships among cold chain technologies, agricultural product categories, and regional features in Western China.

Currently, the agricultural cold chain in Western China faces significant shortcomings in equipment support, digitalization levels, and standardization. A significant research gap lies in the insufficient adaptability between preservation technologies and intelligent algorithms, particularly given the region's diverse scenarios, high-altitude environments, and long transport distances. New technologies such as thermoelectric and thermoacoustic refrigeration can effectively support micro-stations in mountainous

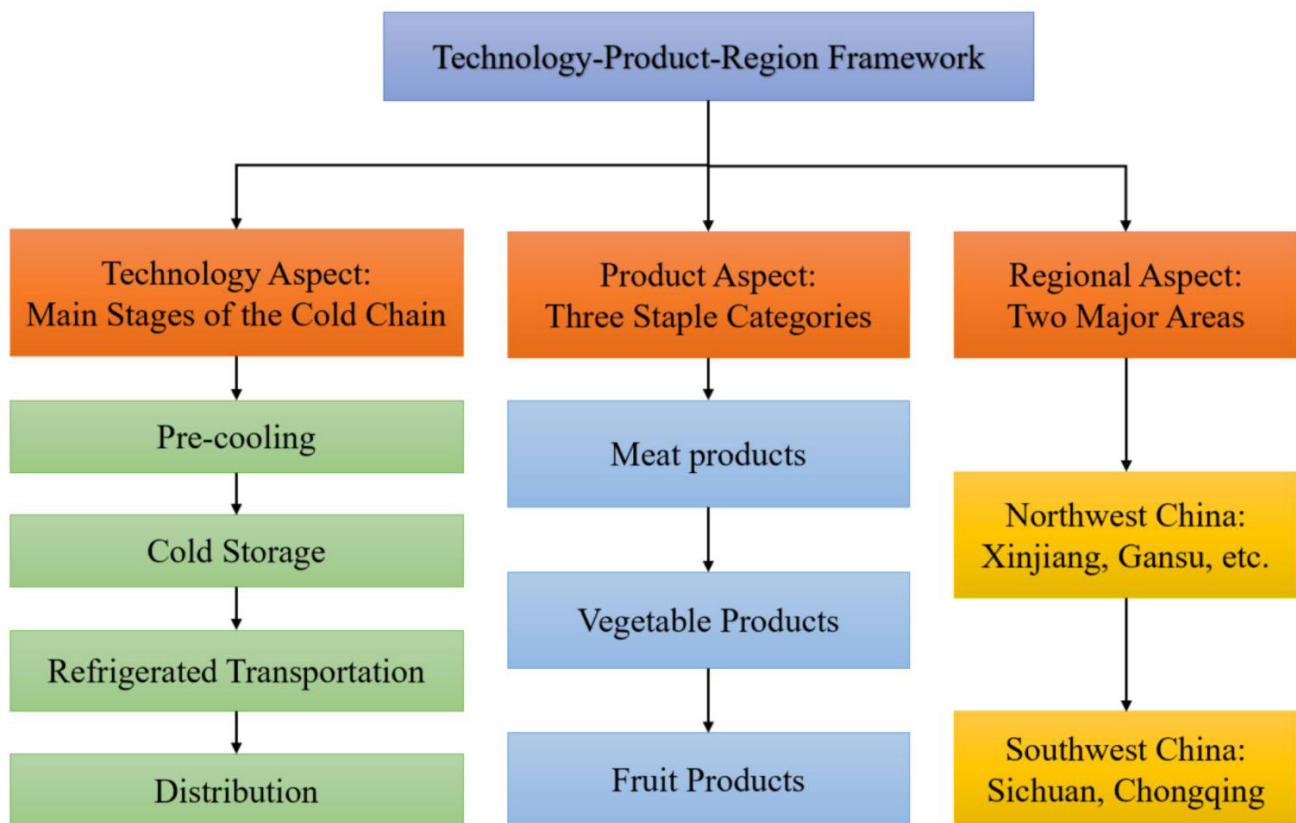


Fig. 6. Analytical diagram of the technology-product-region framework.

areas and remote transportation scenarios, while NFC and Artificial Intelligence of Things (AIoT) technologies will provide technical support for the traceability of geographically indicated products and intelligent scheduling. The synergistic integration of these various technologies will become the core direction for the intelligent upgrading of agricultural product cold chain logistics in Western China.

Based on the industrial realities of agricultural production, this study systematically reviews the current status and trends of cold chain logistics in Western China. The region has developed clear advantages in policy support, resource abundance, and strategic location, with the Four Horizontal and Four Vertical corridors and major land port hubs taking shape.

This study systematically analyzes the development of cold chain logistics in Western China, identifying a complex landscape of strategic advantages and persistent structural bottlenecks. While the region benefits from national policy support and the establishment of key logistics corridors, infrastructure remains geographically imbalanced, with cold storage resources heavily concentrated in provinces like Sichuan and Shaanxi. This leaves remote areas, particularly in the Yunnan-Guizhou and Qinghai-Tibet plateaus, suffering from frequent cold chain disruptions and a lack of unified standards. A comparative analysis of existing literature reveals that delayed pre-cooling, inadequate storage conditions, and disruptions in the transporta-

tion chain are common issues contributing to the generally high cold chain loss rates of agricultural products in Western China. However, the primary bottlenecks in Northwest China are concentrated in the poor flow of cross-border cold chain corridors, uneven distribution of cold storage facilities, and insufficient long-distance temperature control capabilities; whereas Southwest China is more significantly affected by factors such as mountainous terrain, a lack of pre-cooling facilities at production sites, and low efficiency in short-distance distribution. Currently, relevant research remains limited to fragmented analyses by region and logistics stage. A systematic framework for uniformly comparing and evaluating cold chain bottlenecks across regions has not yet been established. Furthermore, the majority of fresh produce is still transported without temperature control, primarily due to the prohibitive cost of refrigerated transport and weak third-party logistics capabilities. Technical applications such as differential pressure pre-cooling, controlled atmosphere storage, and metaheuristic optimization algorithms have proven effective in reducing losses and balancing costs. However, their large-scale adoption is hindered by the scarcity of multidisciplinary talent in rural areas. Consequently, bridging the gap between high-tech potential and the economic realities of small-scale producers remains the central challenge for the industrial upgrading of Western China's agricultural supply chain.

6. Future Prospects

In the future, agricultural logistics in Western China will evolve into a paradigm of intelligence, sustainability, and global integration. Artificial Intelligence (AI) and Big Data will enable precise demand forecasting as a routine practice, while green technologies, such as CO₂ cascade refrigeration, will help drive the industry toward carbon neutrality. To address the unique challenges of high-altitude terrains, the deployment of Low-Earth Orbit (LEO) Satellite IoT will ensure seamless connectivity in uninhabited zones. Furthermore, Edge Computing utilizing Multiphysics Coupling Algorithms will enable real-time local simulation of airflow and temperature dynamics under low-pressure environments, ensuring thermal stability in extremely highland conditions.

Strategically, the Belt and Road Initiative and the Land-Sea New Channel in Western China will densify international routes through overseas warehouses in Central Asia and the Middle East. By integrating with cross-border e-commerce, Western China is likely to address the disparity between its geographical potential and global market value, converting its unique agricultural resources into a sophisticated and high-efficiency economic engine.

7. Limitations

This review lacks empirical validation, as the synoptic scope of a review article precludes primary data collection and field experimentation. Additionally, the assessment of technology suitability remains largely qualitative, without quantitative evaluation of how cold chain technologies perform under the specific high-altitude, low-oxygen conditions prevalent in Western China.

Author Contributions

Conceptualization, YY and YL; methodology, YY and YL; writing and original draft preparation, YY and YL; writing, review and editing, YY and YL; project administration, YL and YY. Both authors have read and agreed to the published version of the manuscript. Both authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

We would like to express our sincere gratitude to the reviewers for their comments and suggestions.

Funding

This research was funded by the National Natural Science Foundation of China, grant number 32102055 and the Young Teachers Research Ability Enhancement Program, grant number BGY2022KY-03QT.

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Xu J. Analysis of Birth Rate and Regional Economic Influencing Factors in Western China. *Asian Journal of Social Science Studies*. 2023; 8: 30–34. <https://doi.org/10.20849/ajsss.v8i1.1325>
- [2] Ya-Feng Z, Min D, Ya-Jing L, Yao R. Evolution characteristics and policy implications of new urbanization in provincial capital cities in Western China. *PloS One*. 2020; 15: e0233555. <https://doi.org/10.1371/journal.pone.0233555>
- [3] Ye Y, Tao Q. The dynamic relationship among economic development, air pollution, and health production in China: the DNSBM efficiency model. *Frontiers in Environmental Science*. 2023; 11. <https://doi.org/10.3389/fenvs.2023.1205712>
- [4] Bird J, Lebrand M, Venables AJ. The Belt and Road Initiative: Reshaping economic geography in Central Asia? *Journal of Development Economics*. 2020; 144: 102441. <https://doi.org/10.1016/j.jdeveco.2020.102441>
- [5] Zhu Z. Trends and Current Situation of China's Meat Sector. *Animal Research and One Health*. 2026; 1–3. <https://doi.org/10.1002/aro2.70055>
- [6] Guo D, Pu H. Evaluation of the Genetic Resource Value of Datong Yak: A Cultivated Breed on the Qinghai–Tibet Plateau. *Agriculture*. 2025; 15: 2114. <https://doi.org/10.3390/agriculture15202114>
- [7] Ding Y, Fu G, Zheng K. Double Agglomeration of the Agricultural Industry, Technological Innovation, and Farmers' Agricultural Incomes: Evidenced by the Citrus Industry. *Sustainability*. 2025; 17: 10651. <https://doi.org/10.3390/su172310651>
- [8] Li X, Wang Z, Wang S, Qian Z. MaxEnt and Marxan modeling to predict the potential habitat and priority planting areas of *Coffea arabica* in Yunnan, China under climate change scenario. *Frontiers in Plant Science*. 2024; 15: 1471653. <https://doi.org/10.3389/fpls.2024.1471653>
- [9] Zhu C. Spatial Distribution Characteristics and Influencing Factors of Geographical Indication Agricultural Products in Shaanxi Province. *International Journal of Global Economics and Management*. 2024; 3: 448–457. <https://doi.org/10.62051/ijgem.v3n1.56>
- [10] Wei X, Li F, Cai D. The Mechanism and Path of New Quality Productivity Empowering the High-quality Development of Yunnan's Plateau Characteristic Vegetable Industry. *Tropical Agricultural Science & Technology*. 2025; 48: 19–28. <https://doi.org/10.16005/j.cnki.tast.20250412> (In Chinese)
- [11] Mercier S, Villeneuve S, Mondor M, Uysal I. Time-Temperature Management Along the Food Cold Chain: A Review of Recent Developments. *Comprehensive Reviews in Food Science and Food Safety*. 2017; 16: 647–667. <https://doi.org/10.1111/1541-4337.12269>
- [12] Sutherland D, Anderson J, Bailey N, Alon I. Policy, institutional fragility, and Chinese outward foreign direct investment: An empirical examination of the Belt and Road Initiative. *Journal of International Business Policy*. 2020; 3: 249–272. <https://doi.org/10.1057/s42214-020-00056-8>
- [13] Mu N, Wang Y, Wang M, Han S, Chen ZS. The Co-evolution of the Regional Logistics Network in the Chengdu–Chongqing Region Based on Node Attraction. *International Journal of Computational Intelligence Systems*. 2022; 15. <https://doi.org/10.1007/s44196-022-00082-9>
- [14] Zhao C. Research on logistics efficiency and influencing factors of cold chain of fresh agricultural products in western China [master's thesis]. Chongqing Jiaotong University: Chongqing. 2024. <https://doi.org/10.27671/d.cnki.gcjtc.2024.001282> (In Chinese)

- [15] Zhou X, Li J, Xie F, Fang J. Research on origin-based cold storage location and routing optimization of fresh agricultural products based on hybrid whale algorithm. *Scientific Reports*. 2024; 14: 21078. <https://doi.org/10.1038/s41598-024-72170-z>
- [16] Simayi A, Wusiman W. Research on the Situation of Xinjiang Agricultural Cold Chain Logistics and Its Development Path. *Prices Monthly*. 2018; 75–78. <https://doi.org/10.14076/j.issn.1006-2025.2018.02.15> (In Chinese)
- [17] Fan X, Zhang Y, Xue J, Cao Y. Exploring the path to the sustainable development of cold chain logistics for fresh agricultural products in China. *Environmental Impact Assessment Review*. 2024; 108: 107610. <https://doi.org/10.1016/j.eiar.2024.107610>
- [18] Guo Z, Chen Y, Wu Y, Zhan S, Wang L, Li L, et al. Changes in meat quality, metabolites and microorganisms of mutton during cold chain storage. *Food Research International (Ottawa, Ont.)*. 2024; 189: 114551. <https://doi.org/10.1016/j.foodres.2024.114551>
- [19] Zhu H, Liu C, Wu G, Gao Y. Cold Chain Logistics Network Design for Fresh Agricultural Products with Government Subsidy. *Sustainability*. 2023; 15: 10021. <https://doi.org/10.3390/su151310021>
- [20] Zhao J. Research on Optimization Strategies for Cold Chain Logistics of Fresh Food in Cross border E-commerce. *Frontiers in Business, Economics and Management*. 2025; 20: 33–38. <https://doi.org/10.54097/wk3ddz34>
- [21] EFSA Panel on Biological Hazards (BIOHAZ), Koutsoumanis K, Allende A, Alvarez-Ordóñez A, Bover-Cid S, Chemaly M, et al. Microbiological safety of aged meat. *EFSA Journal*. European Food Safety Authority. 2023; 21: e07745. <https://doi.org/10.2903/j.efsa.2023.7745>
- [22] Dang DS, Bastarrachea LJ, Martini S, Matarneh SK. Crystallization Behavior and Quality of Frozen Meat. *Foods (Basel, Switzerland)*. 2021; 10: 2707. <https://doi.org/10.3390/foods10112707>
- [23] Talbot L, Purnell G, James SJ, James C. Operating temperatures of supermarket frozen retail display cabinets. *International Journal of Refrigeration*. 2020; 117: 81–93. <https://doi.org/10.1016/j.ijrefrig.2020.04.017>
- [24] Calati M, Hooman K, Mancin S. Thermal storage based on phase change materials (PCMs) for refrigerated transport and distribution applications along the cold chain: A review. *International Journal of Thermofluids*. 2022; 16: 100224. <https://doi.org/10.1016/j.ijft.2022.100224>
- [25] Foster A, Liu G, Xie R, Wu J, Evans J. Design and application of a novel cold chain pallet using a phase change material. *The 25 th IIR International Congress of Refrigeration: Montréal, Canada*. 2019. <https://doi.org/10.18462/iir.icr.2019.0306>
- [26] Wang F, Maidment G, Missenden J, Tozer R. The novel use of phase change materials in refrigeration plant. Part 1: Experimental investigation. *Applied Thermal Engineering*. 2007; 27: 2893–2901. <https://doi.org/10.1016/j.applthermaleng.2005.06.011>
- [27] da Nóbrega Santos E, Cesar de Albuquerque Sousa T, Cassiano de Santana Neto D, Brandão Grisi CV, Cardoso da Silva Ferreira V, Pereira da Silva FA. Edible active film based on gelatin and *Malpighia emarginata* waste extract to inhibit lipid and protein oxidation in beef patties. *LWT*. 2022; 154: 112837. <https://doi.org/10.1016/j.lwt.2021.112837>
- [28] Wu LZ, Zhao Y. Cold Chain Logistics Temperature Monitoring System Based on Internet of Things Technology. *Applied Mechanics and Materials*. 2013; 416-417: 1969–1973. <https://doi.org/10.4028/www.scientific.net/amm.416-417.1969>
- [29] Pattanaik S, Jenamani M. Numerical investigation of temperature heterogeneity during cold chain export: A virtual cold chain approach. *Journal of Food Process Engineering*. 2024; 47. <https://doi.org/10.1111/jfpe.14715>
- [30] Indiarito R, Irawan AN, Subroto E. Meat Irradiation: A Comprehensive Review of Its Impact on Food Quality and Safety. *Foods (Basel, Switzerland)*. 2023; 12: 1845. <https://doi.org/10.3390/foods12091845>
- [31] Badr HM. Use of irradiation to control foodborne pathogens and extend the refrigerated market life of rabbit meat. *Meat Science*. 2004; 67: 541–548. <https://doi.org/10.1016/j.meatsci.2003.11.018>
- [32] Chaomuang N, Flick D, Laguerre O. Experimental and numerical investigation of the performance of retail refrigerated display cabinets. *Trends in Food Science & Technology*. 2017; 70: 95–104. <https://doi.org/10.1016/j.tifs.2017.10.007>
- [33] Duman E, Aydoğan E. Enhancing Traceability and Reliability in Cold Chain Logistics Through Hyperledger Fabric and IoT. *Applied Sciences*. 2025; 15: 12149. <https://doi.org/10.3390/ap152212149>
- [34] Shull C, Marecki K, Huk K, Wolski R. The Study of RFID Technology and Laser Telemetry to Locate Products in Space. *Mobile Networks and Applications*. 2023; 29: 516–532. <https://doi.org/10.1007/s11036-023-02242-3>
- [35] Barge P, Biglia A, Comba L, Ricauda Aimonino D, Tortia C, Gay P. Radio Frequency Identification for Meat Supply-Chain Digitalisation. *Sensors (Basel, Switzerland)*. 2020; 20: 4957. <https://doi.org/10.3390/s20174957>
- [36] Li J, Zhang Y. Design and Accomplishment of the Real-Time Tracking System of Agricultural Products Logistics Process. *2010 International Conference on E-Product E-Service and E-Entertainment*. 2010; 1–4. <https://doi.org/10.1109/iceee.2010.5661130>
- [37] Ren QS, Fang K, Yang XT, Han JW. Ensuring the quality of meat in cold chain logistics: A comprehensive review. *Trends in Food Science & Technology*. 2022; 119: 133–151. <https://doi.org/10.1016/j.tifs.2021.12.006>
- [38] Hang C, Sun S, Zhang H, Rong W, Xu S, Ma G. Experimental study on portable cold storage box with phase change material packages. *Thermal Science*. 2026; 30: 229–238. <https://doi.org/10.2298/tsci250426127h>
- [39] Kumar R, Kumar A, Narayana Murthy U. Heat transfer during forced air precooling of perishable food products. *Biosystems Engineering*. 2008; 99: 228–233. <https://doi.org/10.1016/j.biosystemseng.2007.10.012>
- [40] Alibas I, Koksall N. Forced-air, vacuum, and hydro precooling of cauliflower (*Brassica oleracea* L. var. botrytis cv. Freemont): part I. determination of precooling parameters. *Food Science and Technology (Campinas)*. 2014; 34: 730–737. <https://doi.org/10.1590/1678-457x.6456>
- [41] Xu Q, Wang R, Wang L, Xing Y, Li W, Yang H, et al. Effects of different pre-cooling methods on quality changes in fresh-cut purple cabbage during cold-chain transportation. *Food and Fermentation Industries*. 2019; 45: 135–143. <https://doi.org/10.13995/j.cnki.11-1802/ts.019049> (In Chinese)
- [42] Lal Basediya A, Samuel DVK, Beera V. Evaporative cooling system for storage of fruits and vegetables - a review. *Journal of Food Science and Technology*. 2013; 50: 429–442. <https://doi.org/10.1007/s13197-011-0311-6>
- [43] Ren X, Wu W, Wang Z, Zhu Q. Experimental Investigation on Effects of Ice Slurry Spray Flow Rate on Performance of Wet Cooling Pre-cooling System. *Chinese Journal of Refrigeration Technology*. 2021; 41: 36–42. <https://doi.org/10.3969/j.issn.2095-4468.2021.02.204> (In Chinese)
- [44] Su M, Wu W, Ren X, Li X. Effect of Different Packings on the Performance of Ice-slurry Wet Precooling Storage. *Journal of Refrigeration*. 2022; 43: 145–152
- [45] Becker BR, Fricke BA. Hydrocooling time estimation methods. *International Communications in Heat and Mass Transfer*. 2002; 29: 165–174. [https://doi.org/10.1016/s0735-1933\(02\)00307-x](https://doi.org/10.1016/s0735-1933(02)00307-x)

- [46] Gillies S, Toivonen P. Cooling Method Influences the Postharvest Quality of Broccoli. *HortScience*. 1995; 30: 313–315. <https://doi.org/10.21273/hortsci.30.2.313>
- [47] Tao S, Wang J, Xie J. Influence of different pre-cooling methods on the freshness preservation of bok choy (*Brassica rapa* var. *chinensis*). *Food Chemistry: X*. 2024; 23: 101599. <https://doi.org/10.1016/j.fochx.2024.101599>
- [48] Huang M, Wang L, Kong F, Tian C, Shao W, Zhao J, et al. Vacuum cooling of leafy vegetables: Model, validation and optimization. *Journal of Food Engineering*. 2026; 413: 113022. <https://doi.org/10.1016/j.jfoodeng.2026.113022>
- [49] Liu JY, Liu CW, Chen WL, Hsu MC, Lin HL, Chen CL. Extending Shelf Life of Cabbage (*Brassica oleracea* cv. K-Y Cross) by Using Vacuum Precooling and Modified Atmosphere Packaging. *Horticulturae*. 2023; 9: 1096. <https://doi.org/10.3390/horticulturae9101096>
- [50] He SY, Li YF. Experimental study and process parameters analysis on the vacuum cooling of iceberg lettuce. *Energy Conversion and Management*. 2008; 49: 2720–2726. <https://doi.org/10.1016/j.enconman.2008.04.004>
- [51] Tian D, Fen L, Jiangang L, Mengli K, Jingfen Y, Xingqian Y, et al. Comparison of different cooling methods for extending shelf life of postharvest broccoli. *International Journal of Agricultural and Biological Engineering*. 2016; 9: 178–185. <https://doi.org/10.3965/j.ijabe.20160906.2107>
- [52] Jarman A, Thompson J, McGuire E, Reid M, Rubsam S, Becker K, et al. Postharvest technologies for small-scale farmers in low- and middle-income countries: A call to action. *Postharvest Biology and Technology*. 2023; 206: 112491. <https://doi.org/10.1016/j.postharvbio.2023.112491>
- [53] Praeger U, Jedermann R, Sellwig M, Neuwald DA, Hartgenbusch N, Borysov M, et al. Airflow distribution in an apple storage room. *Journal of Food Engineering*. 2020; 269: 109746. <https://doi.org/10.1016/j.jfoodeng.2019.109746>
- [54] Praeger U, Jedermann R, Sellwig M, Neuwald DA, Truppel I, Scaar H, et al. Influence of room layout on airflow distribution in an industrial fruit store. *International Journal of Refrigeration*. 2021; 131: 714–722. <https://doi.org/10.1016/j.ijrefrig.2021.06.016>
- [55] Bodbodak S, Moshfeghifar M. Advances in controlled atmosphere storage of fruits and vegetables. *Eco-Friendly Technology for Postharvest Produce Quality*. 2016; 39–76. <https://doi.org/10.1016/b978-0-12-804313-4.00002-5>
- [56] Anastasiadi M, Collings ER, Terry LA. Investigating the role of abscisic acid and its catabolites on senescence processes in green asparagus under controlled atmosphere (CA) storage regimes. *Postharvest Biology and Technology*. 2022; 188: 111892. <https://doi.org/10.1016/j.postharvbio.2022.111892>
- [57] Luna MC, Tudela JA, Tomás-Barberán FA, Gil MI. Modified atmosphere (MA) prevents browning of fresh-cut romaine lettuce through multi-target effects related to phenolic metabolism. *Postharvest Biology and Technology*. 2016; 119: 84–93. <https://doi.org/10.1016/j.postharvbio.2016.05.001>
- [58] Wang X, Han Y, Wu W, Liu R, Chen H, Gao Y, et al. Effect of Controlled Atmosphere Storage on Chlorophyll Degradation of Soybeans after Harvest. *Journal of Chinese Institute of Food Science and Technology*. 2023; 23: 191–201. <https://doi.org/10.16429/j.1009-7848.2023.11.019>
- [59] Verreydt C, Anthony B, Tellekson A, Shelly J, Reiter J, Mitchell T, et al. Analyzing and optimizing refrigerated hypobaric storage chambers for lime fruit via multiphysics modeling. *Thermal Science and Engineering Progress*. 2025; 62: 103634. <https://doi.org/10.1016/j.tsep.2025.103634>
- [60] Sang Y, Zhang M, Xiao W. Effect of Hypobaric Storage on Preservation of Three Kinds of Vegetables. *Journal of Food Science and Biotechnology*. 2018; 37: 70–75
- [61] Shen J, Zhang C, Liu S, Ding F. Development of Multifunctional Fresh-keeping Device and Experiment of Cabbage Vacuum Pre-cooling. *Journal of Refrigeration*. 2017; 38: 107–112
- [62] Liu DK, Xu CC, Guo CX, Zhang XX. Sub-zero temperature preservation of fruits and vegetables: A review. *Journal of Food Engineering*. 2020; 275: 109881. <https://doi.org/10.1016/j.jfoodeng.2019.109881>
- [63] Lin B, Lu X, Li J, Chen S. Effect of ice-temperature storage on the freshness retaining of broccolis. *Science and Technology of Food Industry*. 2012; 33: 312–316. <https://doi.org/10.13386/j.isn1002-0306.2012.19.063>
- [64] Deng J, Han C, Wang W, Cao J, Zhou Z, Zhao G, et al. Effects of different storage temperatures on the shelf life and quality characteristics of winter jujubes. *Scientia Horticulturae*. 2026; 355: 114594. <https://doi.org/10.1016/j.scienta.2025.114594>
- [65] Yan C, Liu S, Jia L, Wang D, Zhang X. Research progress on cold chain logistics technique of vegetables. *Food & Machinery*. 2015; 31: 260–265. <https://doi.org/10.13652/j.issn.1003-5788.2015.04.064> (In Chinese)
- [66] Costa C, Antonucci F, Pallottino F, Aguzzi J, Sarriá D, Menesatti P. A Review on Agri-food Supply Chain Traceability by Means of RFID Technology. *Food and Bioprocess Technology*. 2012; 6: 353–366. <https://doi.org/10.1007/s11947-012-0958-7>
- [67] Bai L, Liu M, Sun Y. Overview of Food Preservation and Traceability Technology in the Smart Cold Chain System. *Foods (Basel, Switzerland)*. 2023; 12: 2881. <https://doi.org/10.3390/foods12152881>
- [68] Lamberty A, Kreyenschmidt J. Ambient Parameter Monitoring in Fresh Fruit and Vegetable Supply Chains Using Internet of Things-Enabled Sensor and Communication Technology. *Foods (Basel, Switzerland)*. 2022; 11: 1777. <https://doi.org/10.3390/foods11121777>
- [69] Lifeng W, Fei H, Zhu G-h. Design of Cold Chain Logistics Information Real Time Tracking System Based on Wireless RFID Technology. *Advanced Hybrid Information Processing*. 2022; 440–453. https://doi.org/10.1007/978-3-030-94551-0_35
- [70] Liang H. Present Situation and Development Countermeasures of Postharvest Commercialization Treatment of Vegetables in Beijing [master's thesis]. Guangxi University: Nanning. 2024. <https://doi.org/10.27034/d.cnki.ggxju.2024.002704> (In Chinese)
- [71] Wang X, Chen A, Liu H, Guan W, Liu B. Application of Differential Pressure Pre-cooling Technology and Facility in Cold Chain Logistics of Fruits and Vegetables. *Storage and Process*. 2020; 20: 215–219. <https://doi.org/10.3969/j.issn.1009-6221.2020.04.034> (In Chinese)
- [72] Wang J, Liu S, Wu W, Zhou S, Zhang Q, Zhong Y. Simulation and Experimental Study on Effect of Cucumber Laying Modes on Forced-air Pre-cooling Process. *Chinese Journal of Refrigeration Technology*. 2018; 38: 25–29. <https://doi.org/10.3969/j.isn.2095-4468.2018.05.105> (In Chinese)
- [73] Wu W, Cronjé P, Verboven P, Defraeye T. Unveiling how ventilated packaging design and cold chain scenarios affect the cooling kinetics and fruit quality for each single citrus fruit in an entire pallet. *Food Packaging and Shelf Life*. 2019; 21: 100369. <https://doi.org/10.1016/j.fpsl.2019.100369>
- [74] Di Francesco A, Ippolito A, Romanazzi G. Heat treatments for the control of postharvest decay of fresh fruit: Case studies of peach brown rot, kiwifruit gray mold and citrus green and blue molds. *Postharvest Biology and Technology*. 2026; 231: 113868. <https://doi.org/10.1016/j.postharvbio.2025.113868>
- [75] Gomes BAF, Alexandre ACS, de Andrade GAV, Zanzini AP, de Barros HEA, Ferraz e Silva LMDS, et al. Recent advances in processing and preservation of minimally processed fruits and vegetables: A review – Part 2: Physical methods and global

- market outlook. *Food Chemistry Advances*. 2023; 2: 100304. <https://doi.org/10.1016/j.focha.2023.100304>
- [76] Ma S, Chen L, Peng Y, Shi J. Pre-cut hot water treatment can inhibit the browning of fresh-cut apple by regulating phenylpropanoid pathway metabolism. *Acta Horticulturae*. 2021; 199–208. <https://doi.org/10.17660/actahortic.2021.1319.23>
- [77] Wei Y, Zhou D, Peng J, Pan L, Tu K. Hot Air Treatment Induces Disease Resistance through Activating the Phenylpropanoid Metabolism in Cherry Tomato Fruit. *Journal of Agricultural and Food Chemistry*. 2017; 65: 8003–8010. <https://doi.org/10.1021/acs.jafc.7b02599>
- [78] Xiao X, Wang X, Zhang X, Chen E, Li J. Effect of the Quality Property of Table Grapes in Cold Chain Logistics-Integrated WSN and AOW. *Applied Sciences*. 2015; 5: 747–760. <https://doi.org/10.3390/app5040747>
- [79] Le NT, Thwe Chit MM, Truong TL, Siritantikorn A, Kongrutanachok N, Asdornwiset W, et al. Deployment of Smart Specimen Transport System Using RFID and NB-IoT Technologies for Hospital Laboratory. *Sensors (Basel, Switzerland)*. 2023; 23: 546. <https://doi.org/10.3390/s23010546>
- [80] Onwude D, Bahrami F, Shrivastava C, Berry T, Cronje P, North J, et al. Physics-driven digital twins to quantify the impact of pre- and postharvest variability on the end quality evolution of orange fruit. *Resources, Conservation and Recycling*. 2022; 186: 106585. <https://doi.org/10.1016/j.resconrec.2022.106585>
- [81] Chen YH. Intelligent algorithms for cold chain logistics distribution optimization based on big data cloud computing analysis. *Journal of Cloud Computing*. 2020; 9: 37. <https://doi.org/10.1186/s13677-020-00174-x>
- [82] Xiong H. Research on Cold Chain Logistics Distribution Route Based on Ant Colony Optimization Algorithm. *Discrete Dynamics in Nature and Society*. 2021; 2021: 1–10. <https://doi.org/10.1155/2021/6623563>
- [83] Jia X. Research on the Optimization of Cold Chain Logistics Distribution Path of Agricultural Products E-Commerce in Urban Ecosystem From the Perspective of Carbon Neutrality. *Frontiers in Ecology and Evolution*. 2022; 10. <https://doi.org/10.3389/fevo.2022.966111>
- [84] Song MX, Li JQ, Han YQ, Han YY, Liu LL, Sun Q. Metaheuristics for solving the vehicle routing problem with the time windows and energy consumption in cold chain logistics. *Applied Soft Computing*. 2020; 95: 106561. <https://doi.org/10.1016/j.asoc.2020.106561>
- [85] Qi Z, Xu R, Jing P. Solution to Chilled Meat Distribution Path Based on Modified C-W Algorithm. *Journal of Luoyang Normal University*. 2021; 40: 14–18. <https://doi.org/10.16594/j.cnki.41-1302/g4.2021.05.005> (In Chinese)
- [86] Lee J, Yang J. A Fast and Scalable Re-routing Algorithm based on Shortest Path and Genetic Algorithms. *Journal of Computers Communications & Control*. 2014; 7: 482. <https://doi.org/10.15837/ijccc.2012.3.1389>
- [87] Liu X, Xu J. Simulation Research on Logistics Distribution Path Based on Colony Intelligence Optimisation. *Applied Mathematics and Nonlinear Sciences*. 2024; 9. <https://doi.org/10.2478/amns-2024-1480>
- [88] Feng Q, Zhao G, Li W, Shi X. Distribution Path Optimization of Fresh Products in Cold Storage Considering Green Costs. *Buildings*. 2023; 13: 2325. <https://doi.org/10.3390/buildings13092325>
- [89] Qi C. Multi-objective Optimization-Based Algorithm for Selecting the Optimal Path of Rural Multi-temperature Zone Cold Chain Dynamic Logistics Intermodal Transportation. *International Journal of Computational Intelligence Systems*. 2024; 17. <https://doi.org/10.1007/s44196-024-00616-3>
- [90] Wang C, Hasuike T. Dual-Objective Optimization Model for Low Carbon Cold-Chain Logistics. *Journal of Advanced Computational Intelligence and Intelligent Informatics*. 2026; 30: 532–542. <https://doi.org/10.20965/jaciii.2026.p0532>
- [91] Wang K, Du N. Real-time monitoring and energy consumption management strategy of cold chain logistics based on the internet of things. *Energy Informatics*. 2025; 8. <https://doi.org/10.1186/s42162-025-00493-w>
- [92] Wang Y, Wang Z, Song M, Fang L. Path Optimization of Reefer Container Intermodal Transportation Under Transfer Time Uncertainty. *Journal of Transportation Systems Engineering and Information Technology*. 2025; 25: 124–134. <https://doi.org/10.16097/j.cnki.1009-6744.2025.05.011> (In Chinese)
- [93] Wang Y, Luo S, Gou M, Luo S. Fresh Commodity Logistics Distribution Optimization Considering Dynamic Demands. *Packaging Engineering*. 2024; 45: 148–158. <https://doi.org/10.19554/j.cnki.1001-3563.2024.07.019> (In Chinese)