

Stable Operation Mechanism for Logistics Support of Yichun Agricultural Products Cold Chain under Sudden Disturbances in Low-Altitude Logistics

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Abstract: Fresh cold chain logistics in the hilly western Jiangxi region has long been subjected to multiple sudden disturbances such as geological disasters during flood seasons and road blockages, making it difficult for land-based transportation modes to ensure stable circulation of characteristic agricultural products. This paper selects Yichun as the research object, reviews local cold chain disturbances, analyzes the deficiencies of traditional land-based cold chain systems, and elaborates on the distinct advantages of unmanned aerial vehicle low-altitude logistics under the decentralized production and marketing model in mountainous areas. Four main operation mechanisms are established: hierarchical early warning, capacity dispatching, multi-party coordination, and whole-process temperature control. A practical guarantee system is constructed from four aspects: infrastructure construction, airspace policy, intelligent platform, and talent development.

Keywords: Sudden disturbances; Low-altitude logistics; Agricultural products cold chain; Logistics support; Yichun characteristic agricultural products

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1. Introduction

The integration of the low-altitude economy with the fresh cold chain represents an important pathway for improving quality and reducing losses in rural agricultural product circulation. Characteristic fresh products such as selenium-enriched fruits and vegetables and Chinese medicinal materials are scattered across mountainous areas in Yichun, where seasonal flooding and landslides during flood seasons frequently disrupt rural cold chain road networks. Traditional land-based cold chains demonstrate weak anti-disturbance capabilities, resulting in severe problems of fresh product spoilage and production-marketing chain rupture.

Most current research focuses on drone delivery in plain areas, with limited studies on low-altitude cold chain operation mechanisms under sudden disturbances in hilly and mountainous regions. Therefore, this paper starts from Yichun's local industrial and geographical characteristics to create a complete low-altitude cold

chain operation system suitable for mountainous disturbance scenarios.

2. Disturbance characteristics of Yichun agricultural cold chain and adaptation value of low-altitude logistics

2.1. Localized types of sudden cold chain disturbances in Yichun hilly production areas

Yichun is located in the central hilly area of western Jiangxi, with mountainous counties such as Jing'an, Tonggu, and Fengxin serving as main production areas for characteristic agricultural products. Selenium-enriched fruits and vegetables, alpine kiwifruit, Chinese medicinal materials, and edible fungi are scattered across mountain forests and woodlands. The special terrain and subtropical monsoon climate cause seasonal, high-frequency localized cold chain disturbances. The flood season in this city lasts from April to July each year, when heavy rainfall frequently triggers rockfalls, slope landslides, and waterlogging blockages on rural roads, obstructing land-based outbound transportation channels for mountainous agricultural products and creating regional logistics chain rupture disturbances. Cold chain facilities in remote local townships are insufficient, and prolonged overload operation of pre-cooling facilities at production bases and vehicle-mounted temperature control equipment easily leads to temperature control deviations and equipment failures, disrupting the constant-temperature environment for fresh product storage and transportation, which constitutes equipment-type disturbances ^[1]. During concentrated marketing periods for characteristic agricultural products, cold chain capacity shortages tend to occur. Coupled with poor network signals in deep mountain production areas, digital cold chain monitoring and traceability systems are prone to disconnection, resulting in compound sudden cold chain disturbances interwoven from multiple dimensions including climate, terrain, equipment, capacity, and digital systems.

2.2. Existing shortcomings of Yichun land-based cold chain in responding to sudden disturbances

Currently, Yichun's agricultural product cold chain system relies mainly on traditional land-based refrigerated transportation, which exhibits obvious systemic deficiencies in the complex disturbance environment of hilly and mountainous areas. Most rural cold chain road networks in the municipal area consist of single-line county and township roads with poor traffic resilience and no alternative diversion routes; disasters such as heavy rain and landslides can cause suspension of land-based cold chain operations with no possibility of detour to guarantee supply. Local cold chain enterprises only maintain capacity corresponding to daily production and marketing, lacking adequate emergency reserves, resulting in significant shortfalls in refrigerated capacity and storage-transportation equipment under extreme road conditions, making rapid emergency supply guarantee for fresh products impossible. There are obvious communication barriers among agricultural departments, logistics enterprises, planting cooperatives, and storage entities, with no unified emergency dispatch system in place; response is sluggish, and dispatch is chaotic after disturbances occur.

Sudden disturbances create uncertainty in supply chain network security. Reliable supply chain network design can effectively mitigate risks of node disruption and demand fluctuation, or integrate emergency strategies into supply chain network design to prevent the amplification of interruption risks caused by service level degradation of the entire supply chain when a single node fails. Furthermore, enhancing supply chain emergency response capability is also an effective means of addressing interruption risks; the dynamic capability of supply chains can help the supply chain as a whole adapt to changes in the external environment.

2.3. Advantages of low-altitude logistics in supporting Yichun characteristic agricultural product cold chain

Leveraging the advantages of three-dimensional mobility and strong terrain adaptability of unmanned aerial vehicles, low-altitude logistics can effectively compensate for the deficiencies of land-based cold chains in Yichun's hilly and mountainous areas, aligning well with the stable supply requirements of local agricultural product cold chains. Unconstrained by ground road networks, low-altitude logistics can directly access scattered mountain planting bases, enabling point-to-point rapid transfer of high-value fresh products such as selenium-enriched fruits and vegetables and alpine Chinese medicinal materials, reducing storage and transportation time, and lowering the spoilage rate of agricultural products under sudden disturbances. When land routes are completely blocked and ground capacity falls into a predicament, low-altitude logistics can rapidly fill the gap in aerial capacity, establishing independent aerial cold chain channels to ensure smooth production-marketing chains for agricultural products and resolving the challenge of emergency supply guarantee in mountainous areas. Drone-based cold chains align with the characteristics of small-batch, decentralized sales of local agricultural products, allowing flexible adjustments to storage-transportation methods and temperature control conditions as needed, thereby achieving cold chain protection.

3. Core mechanisms for stable operation of agricultural product cold chain supported by low-altitude logistics under sudden disturbances

3.1. Hierarchical early warning and pre-positioned prevention and control mechanism based on local risks

Based on the seasonal, regional, and compound characteristics of disturbances in Yichun's hilly production areas, a pre-positioned prevention and control system aligned with local risk levels is established, serving as the foundation for low-altitude logistics intervention in cold chain supply guarantee and proactive operational risk prevention. Monitoring data from various sources, including municipal meteorology, mountain road conditions, warehouse temperature control, and low-altitude stations, are integrated to build a unified risk monitoring system, enabling comprehensive capture of various disturbance information such as flooding, landslides, road blockages, equipment failures, and capacity shortages ^[2].

Based on the impact severity of historical disturbance events in the locality, sudden cold chain disturbances are classified into three levels: mild, moderate, and severe. Mild refers to local congestion and short-term weather changes; moderate refers to rockfalls and continuous rainfall causing local chain ruptures; severe refers to landslides and full-section flooding resulting in complete suspension of land-based operations. Different early warning push and pre-positioned disposal procedures are adopted according to different risk levels. Through the digital platform, early warning information is synchronously pushed to agricultural departments at municipal, county, and township levels, low-altitude logistics enterprises, planting cooperatives, and storage entities. For mild risks, capacity is diverted in advance; for moderate risks, low-altitude capacity is pre-positioned and deployed; for severe risks, the territory-wide low-altitude supply guarantee contingency plan is immediately activated.

3.2. Dynamic air-land capacity dispatch mechanism adapted to mountain road conditions

Given the complex road conditions in Yichun's hilly and mountainous areas, the poor resilience of land-based capacity, and the reality that sudden disturbances easily cause chain ruptures, an air-land integrated, dynamically

switched, and intelligently adapted capacity dispatch mechanism is established to achieve optimal allocation of cold chain capacity under both normal operations and emergency disturbances. Resource reconfiguration capability is also a sub-capability of dynamic capability, enabling enterprises to form a “dynamic optimization” state with internal and external resources and capabilities.

Under normal stable production-marketing conditions and minor disturbances, the system adopts a trunk-branch integrated approach of “land-based trunk lines as primary, low-altitude terminal supplementation,” with refrigerated trucks undertaking bulk county-level trunk transfer tasks and drones executing short-distance delivery from scattered mountain bases. When road congestion occurs, the system mobilizes low-altitude logistics to share fresh product orders, thereby alleviating pressure on land-based capacity and preventing fresh product stagnation. During moderate and severe land-based chain rupture disturbances, the system automatically switches to supply guarantee mode, transforming low-altitude logistics into the primary transportation force. Relying on pre-established emergency routes in mountainous areas, township connection points, and backup takeoff-landing nodes within the municipal territory, an aerial express channel is established from mountain bases directly to county-level cold chain hubs, completely replacing paralyzed land-based capacity. Flight routes, capacity deployment scale, and delivery frequency are dynamically adjusted based on Yichun’s mountainous terrain, meteorological changes, and disturbance coverage scope to achieve intelligent dispatching of air-land capacity.

3.3. Multi-party collaborative supply guarantee mechanism spanning municipal, county, and township domains

To address the practical dilemmas of fragmented entities, unclear responsibilities and authorities, poor coordination, and disconnected linkages in Yichun’s agricultural product cold chain emergency supply guarantee, a multi-party collaborative supply guarantee mechanism at municipal, county, and township levels is established, forming a clearly stratified, well-defined, and territory-wide integrated low-altitude cold chain emergency operation pattern.

The mechanism defines the primary functions of entities at each level: municipal agriculture, airspace management, and transportation logistics departments serve as top-level coordinators for overall planning, airspace coordination, policy guidance, and global dispatching, responsible for integrating municipal low-altitude cold chain resources, initiating contingency plans, and exercising unified command under sudden disturbance scenarios; county-level cold chain hubs and low-altitude logistics operating enterprises serve as core storage and transportation entities, responsible for core operations including drone maintenance, aerial transfer, air-land connection, and warehousing and transshipment; township agricultural cooperatives and village-level planting bases serve as entities for agricultural product pre-cooling and sorting, standardized loading, and terminal docking. The three-level linkage forms an operational system.

During emergency supply guarantee periods under sudden disturbances, standardized collaborative operational procedures are strictly implemented, ensuring seamless docking throughout the entire process of fresh product sorting, constant-temperature loading, low-altitude transfer, and warehousing storage, preventing quality losses caused by operational disconnections ^[3]. Meanwhile, priority supply guarantee measures for disturbance scenarios are adopted for high-value characteristic fresh products such as Yichun selenium-enriched kiwifruit, alpine Chinese medicinal materials, and ecological edible fungi.

3.4. Whole-process temperature control closed-loop management mechanism aligned with fresh product characteristics

Based on the preservation characteristics and storage-transportation requirements of local characteristic fresh agricultural products in Yichun, as well as the operational features of cold chains in mountainous areas, a full-process closed-loop, traceable, and adjustable low-altitude cold chain temperature control management system is established, effectively addressing critical problems such as temperature control failure, quality degradation, and increased losses caused by sudden disturbances. Standardized airborne constant-temperature refrigeration equipment suitable for low-altitude flight is selected according to the differentiated preservation thresholds of fruits and vegetables, Chinese medicinal materials, and edible fungi; temperature and humidity ranges for storage and transportation are set by zones and layers. Onboard sensing equipment is utilized for whole-process collection of temperature and humidity data, equipment status, and flight data; the management platform monitors in real time, automatically issuing early warnings and guiding emergency landing at the nearest available site when temperature control deviations or equipment failures are detected, thereby proactively mitigating temperature control risks.

The system establishes a seamless temperature control connection system for air-land transfer, unifying temperature control standards for airborne refrigerated containers, land-based refrigerated vehicles, and county-level cold storage facilities, reducing temperature fluctuations during transfer caused by divergent temperature control standards and lowering fresh product losses. For special circumstances arising from sudden disturbances such as route changes, flight delays, and equipment anomalies, temperature control emergency response plans are formulated, employing methods including rapid equipment replacement, parameter fine-tuning, and shortened transfer times to maintain the effectiveness of cold chain closed-loop control.

4. Implementation guarantee system for Yichun low-altitude cold chain anti-disturbance operation mechanism

4.1. Optimizing municipal low-altitude cold chain emergency infrastructure layout

Based on Yichun's hilly and mountainous industrial layout and high-incidence cold chain disturbances, municipal low-altitude cold chain infrastructure is rationally planned to provide hardware support for the anti-disturbance operation system. Relying on mountainous agricultural product main production areas such as Jing'an, Tonggu, and Fengxin, small-scale drone takeoff-landing points, fresh product pre-cooling and sorting stations, and cold chain material reserve points are established to complete the terminal coverage of low-altitude cold chain throughout the mountainous areas. Specialized low-altitude connection stations are constructed at cold chain hubs in various cities and counties, integrating functions including equipment maintenance, constant-temperature loading and unloading, fresh product transshipment, and emergency landing, enabling seamless air-land cold chain docking ^[4]. Emergency landing and temperature control supply points are arranged along mountain trunk routes to establish an infrastructure network with strong emergency response capabilities.

4.2. Constructing low-altitude general aviation policy system adapted to western Jiangxi airspace

Based on western Jiangxi airspace management regulations and Yichun's agricultural low-altitude cold chain development, a standardized, emergency-oriented, and long-term general aviation policy system is established to provide institutional guarantees for stable low-altitude cold chain operations. Dedicated flight airspace

for agricultural product cold chains is designated, and routine flight reporting procedures are simplified to ensure normal operations of regular distribution. Emergency general aviation green channels are opened for sudden situations such as heavy rain, flooding, and road collapses, reducing emergency flight approval time and accelerating supply guarantee response speed. Industrial support policies are introduced, providing fiscal subsidies for mountain station construction, temperature control equipment procurement, and emergency operations.

4.3. Establishing intelligent control system integrated with local agricultural product traceability

A municipal low-altitude cold chain intelligent control system is established through digital technology, deeply integrated with Yichun's existing agricultural product traceability platform, achieving intelligent control and traceability management of the entire cold chain process under sudden disturbances. The system integrates functional modules including risk early warning, capacity dispatching, flight control, temperature control traceability, and emergency decision-making, concentrating data from meteorology, roads, equipment, and capacity to achieve risk assessment, resource allocation, and route optimization. Through integration with the local traceability system, full-chain data tracing is conducted throughout the entire process from agricultural product pre-cooling and sorting, low-altitude transfer to warehousing and circulation, recording the operational status of the cold chain during each emergency supply guarantee process. The system can utilize historical emergency supply guarantee data to review and identify shortcomings.

4.4. Improving local talent cultivation system for low-altitude cold chain practical operation and maintenance

Based on the actual needs of Yichun's low-altitude cold chain daily operations and emergency supply guarantee, a localized professional practical talent cultivation system is established to provide human resources support for mechanism implementation. School-enterprise cooperation is conducted for core positions including drone operation, equipment maintenance, emergency dispatching, and fresh product temperature control, with practical low-altitude cold chain courses in mountainous areas jointly developed with local vocational schools to cultivate localized skilled talents in a targeted manner. Regular emergency drills are conducted simulating various disturbance scenarios such as road interruptions, floods, and temperature control failures, with multi-party participation to enhance personnel emergency response capabilities. A grassroots talent deployment mechanism is implemented, dispatching operation and maintenance personnel to mountainous agricultural production areas to solidify the talent foundation for low-altitude cold chain operations and emergency supply guarantee.

5. Conclusion

The unique geographical and climatic characteristics of western Jiangxi's hilly and mountainous areas create compound cold chain disturbances interwoven from climate, equipment, and capacity dimensions, rendering single land-based cold chain models insufficient to meet various emergency supply demands. Low-altitude logistics can effectively compensate for deficiencies in traditional circulation systems. Emergency capability for supply chain interruption risks is constituted by multiple interrelated and diverse factors. Therefore, due to the long-term impact of supply chain interruption risks, a stable emergency framework needs to be established,

organizing all emergency supply chain departments and links to achieve horizontal and vertical integrated management of emergency supply chains, forming a complete emergency supply chain system. The closed-loop operation system comprising hierarchical early warning, air-land collaborative dispatching, multi-party coordinated supply guarantee, and whole-process temperature control, supported by multiple guarantee measures including infrastructure, general aviation policies, digitalized control, and local talent cultivation, can ensure sustained and stable fresh product distribution under disturbance environments. Future research may expand the investigation scope to compare cold chain practices in various hilly regions.

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