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Optimizing the logistics and warehousing model of anti-cancer drugs for cancer patients

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Abstract: Against the backdrop of “dual carbon” targets and the upgrading of the health industry, the transformation of anti-cancer drug warehousing models profoundly impacts the psychosocial experience, treatment behavior, and ethical concerns of cancer patients. This study transcends traditional environmental and efficiency perspectives, delving into the complex effects of different warehousing models (centralized, distributed, and hospital-operated) on patient medication adherence, treatment confidence, anxiety levels, disease perception, and the burden of family care. We recognize that the layout of warehousing facilities, delivery timeliness, and drug temperature stability are not merely logistical issues, but core psychosocial factors concerning patients’ sense of security regarding treatment continuity, hope for survival, and dignified care. This paper proposes and validates a fusion-optimized “dynamic adaptive” framework, whose core value lies in: significantly shortened delivery time directly alleviating waiting anxiety for patients and their families; enhanced temperature control stability improving treatment trust and adherence; and optimized network layout potentially reducing the economic and energy burden on families in obtaining medication. The research shows that while achieving carbon emission reduction targets, this model’s more important contribution lies in indirectly but powerfully supporting patients’ mental health, treatment adherence, and quality of life by improving drug accessibility and reliability, particularly significant in palliative care and supportive care scenarios. This study provides a practical path for the transformation of healthcare logistics. Its core lies in the deep integration of environmental sustainability with essential psychosocial support, behavioral facilitation, and ethical considerations (such as equitable access and burden reduction) in cancer care. It emphasizes the crucial role of patient- and family-centered, multidisciplinary collaboration (including oncology, psychology, nursing, and social work) in building resilient healthcare systems.

Keywords: Dual carbon; anti-cancer drugs; logistics and warehousing; model optimization; low-carbon transformation

1. Introduction

Against the intersecting backdrop of China’s “dual carbon” strategy—carbon peaking by 2030 and carbon neutrality by 2060—and the multidimensional health needs of cancer patients, the low-carbon transformation of anti-cancer drug logistics and warehousing has become a dual issue concerning both environmental sustainability and humanistic care. This argument is consistent with wider evidence that healthcare systems and the pharmaceutical industry contribute substantially to environmental footprints and therefore require targeted decarbonization strategies [1–5].

At present, the high energy consumption of cold-chain warehousing, with annual

carbon emissions reaching 870,000 tonnes and increasing by 12% per year, stands in sharp tension with the increasingly prominent psychosocial burden experienced by cancer patients. Recent pharmaceutical logistics research also emphasises that distribution emissions should be measured systematically across both warehousing and transport processes [6]. Existing evidence indicates that a 34% imbalance rate between drug supply and demand, together with a 12% cold-chain failure rate, significantly exacerbates patients' anxiety levels, reduces medication adherence, and undermines doctor-patient trust through three pathways: uncertainty in drug accessibility, crises in treatment confidence, and increased family caregiving burden. Specifically, these effects are reflected in a 21.3-point increase in STAI scores, a decline in medication adherence with an odds ratio of 2.17, and a 38% decrease in the TCPS scale.

Notably, warehousing and logistics function as a critical psychosocial interface through which patients engage with the healthcare system. The choice of warehousing model—centralised, distributed, or self-operated—directly affects patients' illness perception, treatment persistence, and dignity in survival. This is particularly relevant because medication adherence and persistence among cancer patients remain major clinical challenges, especially for oral anticancer therapies that require continuous access and patient confidence in treatment reliability [7–9]. However, existing studies have predominantly focused on technical efficiency, while systematically neglecting the deeper impacts of warehousing optimisation on patients' psychosocial well-being and ethical equity.

Existing literature contains a considerable body of research on pharmaceutical warehousing. For example, Lin et al. [10] summarised the practical experience of applying a hospital information system under a medical consortium model to unified pharmaceutical warehousing and dispensing in their hospital, and analysed its implementation effects, the significance of pharmaceutical warehousing reform under this model, and its existing limitations. Zhao [11] systematically introduced the basic concepts of pharmaceutical warehousing management and distribution management, including drug receipt and warehousing, drug storage and maintenance, drug outbound management, order picking for pharmaceutical distribution, and transportation management in pharmaceutical distribution. Wang [12] examined the development status of China's pharmaceutical cold chain and relevant domestic and international studies on pharmaceutical cold chains, established an evaluation system for pharmaceutical cold-chain warehousing quality using the Balanced Scorecard, and proposed corresponding recommendations for quality improvement. Wang [13], based on the current development of the pharmaceutical industry, reviewed existing literature and data, organised relevant information from various journals, identified existing problems, and proposed innovative strategies for pharmaceutical logistics in order to help pharmaceutical logistics enterprises make appropriate judgements and assessments under the new development context. Pan [14] conducted a detailed analysis of the significance and characteristics of pharmaceutical warehousing quality management, identified existing problems in pharmaceutical warehousing quality management, and proposed optimisation strategies for improving such management.

Provenzani and Di Maria [15] explored the challenge of maintaining stable drug storage throughout the entire process from the pharmacy to the patient's home. Drug stability is directly related to efficacy and safety. Although pharmacists can maintain drug stability within pharmacies by strictly following regulations and precisely controlling temperature, humidity, light, and other conditions, it is highly

challenging for patients to maintain the same conditions at home. Tran et al. [16] focused on regulating drug retention and release through surface anchoring, based on the hyperthermic and photothermal effects of $\text{Fe}_3\text{O}_4\text{-SiO}_2$ core-shell mesoporous nanoparticles. Perry and Gouveia [17] proposed that safe drug storage methods are essential for maintaining optimal standards of animal care, while practical clinical challenges may affect their uptake, thereby influencing drug efficacy and treatment success. Zhuang and Yang [18] summarised on-site inspection findings regarding warehousing management among selected pharmaceutical wholesale enterprises in Shandong Province, identified risks in pharmaceutical warehousing management, and analysed common problems in enterprise warehousing management, with the aim of providing references for pharmaceutical regulation and for pharmaceutical wholesale enterprises to conduct warehousing management in a scientific and compliant manner.

Research on the low-carbon development of pharmaceutical cold chains has mainly focused on the following aspects. The European Union's Good Distribution Practice for Medicinal Products requires pharmaceutical cold-chain warehousing carbon emissions in 2025 to be reduced by 20% compared with 2020, and related studies have focused on the application of renewable energy and intelligent temperature-control technologies. The Mayo Clinic in the United States has shortened the regional distribution radius of anti-cancer drugs to 150 kilometres through the optimisation of a distributed warehousing network, thereby effectively reducing carbon emissions. Zhang et al. [19] analysed the demand characteristics of indoor environmental parameters in pharmaceutical cool-storage warehouses. Focusing on energy conservation and low-carbon development, they fully explored and utilised Chongqing's meteorological advantages, proposed suitable air-treatment solutions, terminal equipment and airflow distribution schemes, and cooling-source solutions, and formulated low-carbon operational control strategies. Zhao et al. [20] found that carbon-reduction behaviours, including waste recycling, investment in environmental protection facilities, and management-based energy conservation, can significantly improve corporate carbon performance. Waste recycling and management-based energy conservation can also significantly enhance corporate innovation performance, with carbon performance playing a mediating role; a dynamic and positive cycle exists among the three.

However, existing studies on low-carbon logistics and warehousing for anti-cancer drugs remain limited, and there is a lack of systematic analysis of the synergistic relationship among "low carbon, safety, and efficiency". In summary, the existing literature has two main limitations. First, it does not fully consider the specific characteristics of anti-cancer drugs, such as their higher requirements for temperature-control precision. Second, the practical applicability of low-carbon optimisation strategies remains relatively weak. On the basis of integrating domestic and international experience, and in combination with the characteristics of anti-cancer drugs, this paper constructs a targeted optimisation scheme for warehousing models.

The innovations of this paper are mainly reflected in the following two aspects. First, it constructs a three-dimensional synergistic research framework of "low carbon, safety, and efficiency". This framework breaks through the limitation of existing studies that mostly focus on a single dimension. In response to the special characteristics of anti-cancer drugs, including high temperature-control precision and strong time sensitivity, it incorporates the dual carbon goals, medication safety, and logistics efficiency into a unified analytical system.

Second, this paper proposes an integrated “dynamic adaptive” optimisation scheme. It innovatively designs a mechanism that combines a “1+N” distributed warehousing system with blockchain-based carbon-footprint traceability. This design also responds to the broader trend of sustainable digitalisation in pharmaceutical supply chains, where digital systems are increasingly used to enhance operational resilience, transparency, and sustainability [21]. Under the premise of ensuring a temperature-control precision of $\pm 0.5^{\circ}\text{C}$, this scheme enables the seamless integration of low-carbon transformation and actual operations, thereby providing pharmaceutical enterprises with a transformation pathway that combines safety and practical feasibility.

This study comprehensively adopts the following three research methods.

(1) Literature review

This study systematically reviews relevant domestic and international literature on dual-carbon logistics, anti-cancer drug warehousing, pharmaceutical cold-chain management, and psychosocial oncology. It integrates industry standards, policy documents, and frontier research findings. By summarising the strengths and limitations of existing studies, this method clarifies the research boundaries and innovative direction of the present study, providing solid theoretical support and literature-based evidence for constructing the warehousing model optimisation framework, analysing key problems, and proposing strategies.

(2) Field interviews

Five pilot units, including pharmaceutical cold-chain enterprises and tertiary oncology hospitals, are selected for field investigation and in-depth interviews. Interviews are conducted with warehousing operation managers, cold-chain technicians, and medical administrators. Real operational data on energy consumption, carbon emissions, delivery timeliness, and equipment operation and maintenance across the three warehousing models are collected on site. This method helps identify current operational pain points and practical challenges in low-carbon transformation, thereby ensuring the authenticity and credibility of the research data.

(3) Questionnaire survey

Cancer patients from collaborating oncology hospitals are selected as survey participants, and a standardised scale-based questionnaire is designed. The survey collects data on patients’ medication-related anxiety, treatment adherence, doctor-patient trust, and family caregiving burden, providing empirical support for evaluating the humanistic benefits of warehousing optimisation. The inclusion of patient-centred outcomes is also consistent with evidence that patient-reported outcome monitoring can improve the evaluation of cancer care quality and patient well-being [22].

2. Analysis of the current status of anticancer drug logistics and warehousing under the dual carbon background

2.1. Warehousing model types and characteristics

There are currently three common models for the logistics and warehousing of anti-cancer drugs in China.

(1) Centralised warehousing

Centralised warehousing is organised around large regional distribution centres, typically located in first-tier cities such as Beijing, Shanghai, Guangzhou, and Shenzhen. In theory, such centres can cover a distribution radius of more than 500

km, while pilot data show an average actual delivery radius of 482 km. By relying on large-scale centralised procurement, the fixed warehousing cost per individual drug item can be reduced by 19%. However, long-distance trunk cold-chain transportation increases carbon emissions, with pilot data showing unit carbon emissions of 4.2 kg per item of medicine. In remote county-level areas, the average delivery time reaches 72 hours, with a delay rate of 11.7%. The advantage of this model lies in the use of large-scale equipment, with the average coefficient of performance (COP) of refrigeration units reaching 2.55.

This model relies on large-scale warehousing facilities and achieves significant economies of scale through centralised procurement and unified inventory management, thereby substantially reducing unit warehousing costs. However, location-routing studies in cold-chain logistics suggest that network configuration and delivery routing are closely related to the overall carbon footprint of distribution systems [23]. Its advantages include high inventory concentration, which facilitates quality traceability and expiry-date management, as well as the optimisation of inventory structures through big-data analysis. However, its limitations are also evident. Long-distance transportation leads to extended delivery distances and higher carbon emissions during the transportation process, which is inconsistent with the green logistics trend under the “dual carbon” goals. Meanwhile, the high delay rate in remote areas makes it difficult to meet the strong timeliness requirements of anti-cancer drugs and may affect the timely access of patients to medication. In summary, this model is characterised by core warehouses located in first-tier central cities, while its main weaknesses are high carbon emissions from long-distance transportation and insufficient last-mile delivery efficiency.

(2) Distributed warehousing

Distributed warehousing establishes multiple forward warehouses in second- and third-tier cities, forming a collaborative network between central warehouses and forward warehouses. Before pilot optimisation, the average delivery radius was 296 km, and the proportion of long-distance trunk transfers decreased. The measured unit carbon emission was 2.8 kg per item of medicine. However, this model also has shortcomings. Multiple warehouses require repeated configuration of cold-chain equipment, and the COP of equipment in individual forward warehouses is only 2.2. Idle equipment increases fixed energy consumption, while dispersed inventory leads to an inventory backlog rate of 8.3% for slow-moving drugs.

This model can effectively shorten delivery distances, reduce transportation-related carbon emissions, and respond more flexibly to changes in market demand. However, because each forward warehouse needs to be independently equipped with cold-chain equipment, warehousing management systems, and specialised personnel, it may result in duplicated construction of warehousing facilities and increased fixed energy consumption. At the same time, dispersed inventory across multiple warehouses may reduce overall inventory turnover and increase the risk of inventory backlog.

(3) Hospital self-operated warehousing

Hospital self-operated warehousing refers to storage facilities built and managed by large oncology hospitals to directly serve their own patients. Such warehouses are usually located close to diagnosis and treatment areas and are equipped with dedicated cold-chain cabinets and emergency reserve areas. This enables anti-cancer drugs to be accessed on demand, with delivery times generally below four hours,

making the model particularly suitable for the rapid allocation of emergency anti-cancer drugs.

However, its limitations are also clear. Due to space constraints within hospitals, the scale of such warehousing is generally small. Refrigeration equipment mostly consists of small independent units, with a coefficient of performance (COP) of only 1.8–2.2, lower than the industry average of 2.5, resulting in relatively high carbon emissions per item of medicine. In addition, the lack of a professional logistics management system leads to low inventory turnover efficiency and makes the model prone to short-term stockouts or excessive reserves.

2.2. Major sources of carbon emissions

(1) Facility energy consumption

Refrigeration systems are the primary source of carbon emissions in anti-cancer drug warehousing. Similar cold-chain studies have shown that refrigeration demand, temperature maintenance, and cold losses are central contributors to climate impacts in temperature-controlled logistics systems [24,25]. Among them, compressors consume a large proportion of electricity in order to maintain a constant temperature of 2–8°C, accounting for 67% of total warehousing energy consumption. Explosion-proof lighting and ventilation systems account for 19%, while cooling losses through the building envelope account for 14%.

(2) Transportation connection

Short-distance transportation between warehousing nodes and distribution terminals generates relatively high carbon emissions. During the unloading process at hospitals, refrigerated vehicles must continue operating to maintain low temperatures for the medicines. The average waiting time reaches 40 minutes, resulting in considerable energy waste. During peak periods at primary-level hospitals, queuing time can reach 90 minutes. Carbon emissions from short-distance transfer account for 23% of total transportation-related emissions across the entire chain, further increasing the carbon emissions per delivery unit.

(3) Inventory management

Excessive inventory leads to a low utilisation rate of refrigerated storage space. As a result, refrigeration systems consume energy for redundant storage space, significantly increasing the refrigeration cost per unit of medicine. Conversely, insufficient inventory may trigger emergency stock transfers, which increase carbon emissions from cross-regional transportation. Moreover, emergency transportation often relies on air freight, whose carbon emissions are 6.8 times higher than those of land transportation. In pilot enterprises, additional carbon emissions caused by unreasonable inventory account for 15% of total emissions.

2.3. Transition pressures under dual carbon targets

Driven by both policy and market forces, the low-carbon transformation of anti-cancer drug logistics and warehousing has become an inevitable trend. At the policy level, the 14th Five-Year Plan for the Development of the Pharmaceutical Industry clearly states that, by 2025, the carbon emission intensity of pharmaceutical cold-chain logistics should decrease by 13.5% compared with 2020. This mandatory target has compelled enterprises to upgrade their warehousing facilities and transportation networks. At the market level, the medical insurance payment system is gradually shifting towards low-carbon healthcare services. In some regions, the full-chain carbon footprint of pharmaceuticals has already been incorporated into bidding

evaluation systems, making carbon emission data one of the core competitive factors for enterprises in tendering processes.

However, the special attributes of anti-cancer drugs impose strict constraints on emission reduction. Their active ingredients are highly sensitive to temperature, and temperature fluctuations during storage and transportation must be controlled within $\pm 0.5^{\circ}\text{C}$. This makes it difficult to directly apply certain mature low-carbon technologies. For example, although new photovoltaic cold-chain equipment can reduce electricity consumption, insufficient power-generation stability may lead to temperature fluctuations. Similarly, while shared warehousing can improve space utilisation, it also increases the risk of cross-contamination among drugs. These factors create a transformation dilemma between “emission-reduction pressure” and the “bottom line of safety”.

3. Diagnosis of existing problems in the logistics and warehousing model of anti-cancer drugs

3.1. The network layout is unreasonable and the carbon footprint remains high

The imbalance in network layout directly increases the overall carbon footprint. This problem is consistent with cold-chain location-routing research showing that poor spatial allocation of logistics nodes can increase delivery distances, energy use, and carbon emissions [23]. In China, the density of warehousing nodes in the eastern region exceeds the optimal level, while the layout in the central and western regions remains sparse. Pilot data show that there are 3.2 warehousing outlets per 100 kilometres in East China, compared with fewer than 0.7 in the western region. As a result, 71% of anti-cancer drugs in central and western China rely on long-distance trunk-line transfers.

Moreover, there is no dynamic inventory linkage mechanism between central warehouses and forward warehouses. Under sudden demand fluctuations, emergency air transportation occurs frequently, leading to an additional increase of more than 30% in carbon emissions.

3.2. Facilities and equipment have a low degree of carbonization and poor energy efficiency

The low-carbon upgrading of facilities and equipment remains delayed, resulting in poor energy-efficiency performance. Most small and medium-sized warehousing enterprises still rely on traditional refrigeration equipment, with relatively low energy-efficiency levels and a clear energy-consumption gap compared with advanced equipment.

Among the interviewed small and medium-sized warehousing enterprises, 62% still use outdated piston refrigeration compressors without variable-frequency energy-saving control. The pilot adoption rate of low-carbon equipment, such as photovoltaic systems and CO_2 transcritical refrigeration, remains below 14%. In addition, manual temperature-control management can result in temperature deviations of up to $\pm 1.2^{\circ}\text{C}$, while the frequent start-stop operation of refrigeration equipment leads to ineffective energy consumption.

3.3. Operation and management are extensive and low-carbon potential has not been realized

The extensive and relatively inefficient mode of operational management has prevented the full exploitation of low-carbon potential. Studies on sustainable

digitalisation in pharmaceutical supply chains suggest that digital integration and process visibility are important for reducing operational inefficiencies and improving sustainability performance [21]. Inventory management still relies heavily on traditional experience-based approaches, resulting in slow inventory turnover and persistently high carbon emissions during the inventory-holding process.

Traditional experience-based stock preparation leads to small-scale stockouts of Class A high-value targeted drugs, while large quantities of Class C rare drugs remain overstocked. In addition, cold-storage doors lack intelligent sensing and control systems, and frequent door opening causes approximately 12% cooling loss. Furthermore, 85% of pharmaceutical enterprises have not established a full-chain carbon-footprint traceability system, making it impossible to accurately calculate carbon emissions at each stage of the process. Blockchain-based supply chain studies indicate that distributed ledgers can support transparency, traceability, data integrity, and sustainability governance when organisational requirements and implementation conditions are properly addressed [26–30].

4. Dual-carbon-oriented optimization strategy for anticancer drug logistics and warehousing

4.1. Network layout optimization: building a "dynamically adaptive" warehouse distribution network

(1) Node Planning based on patient density

Using the centroid method and GIS spatial analysis, combined with cancer incidence data (e.g., the incidence rate in the eastern region is 340/100,000, higher than 280/100,000 in the western region), the location of warehouse nodes is optimized. This approach is consistent with carbon-aware cold-chain location-routing optimisation, which links facility location decisions, route planning, and emission reduction [23]. The formula is as follows:

$$X_0 = \frac{\sum_{i=1}^n Q_i X_i}{\sum_{i=1}^n Q_i} \quad (1)$$

$$Y_0 = \frac{\sum_{i=1}^n Q_i Y_i}{\sum_{i=1}^n Q_i} \quad (2)$$

(X_0, Y_0) is the coordinate of the optimal warehouse center;

Q_i is responsible for the demand for anti-cancer drugs in region i ;

(X_i, Y_i) is represents the geographical coordinates of region i .

After implementation: A province in Central China used this formula to select locations for pre-positioned warehouses in 5 prefecture-level cities. After optimization, the average delivery radius of the province was reduced from 412 km to 287 km, and carbon emissions from trunk transportation decreased by 14.3% year-on-year.

(2) "1+N" distributed warehousing system

The system employs a structure of one regional central warehouse (responsible for long-term storage and overall coordination) and N city-level forward warehouses (responsible for short-term turnover). Big data is used to predict patient needs and dynamically adjust inventory allocation. Such data-driven coordination reflects the role of digitalised supply chains in improving responsiveness, sustainability, and resource allocation in pharmaceutical logistics [21]. For example, the central

warehouse stores long-shelf-life medications (such as targeted therapies with a 2-year shelf life); the forward warehouses store short-term medications (such as chemotherapy adjuvants with a 6-month shelf life). This “1+N” distributed warehousing system effectively improves inventory turnover, reduces cross-regional transfers, and decreases carbon emissions. The “1+N” distributed warehousing system is illustrated **Figure 1**.

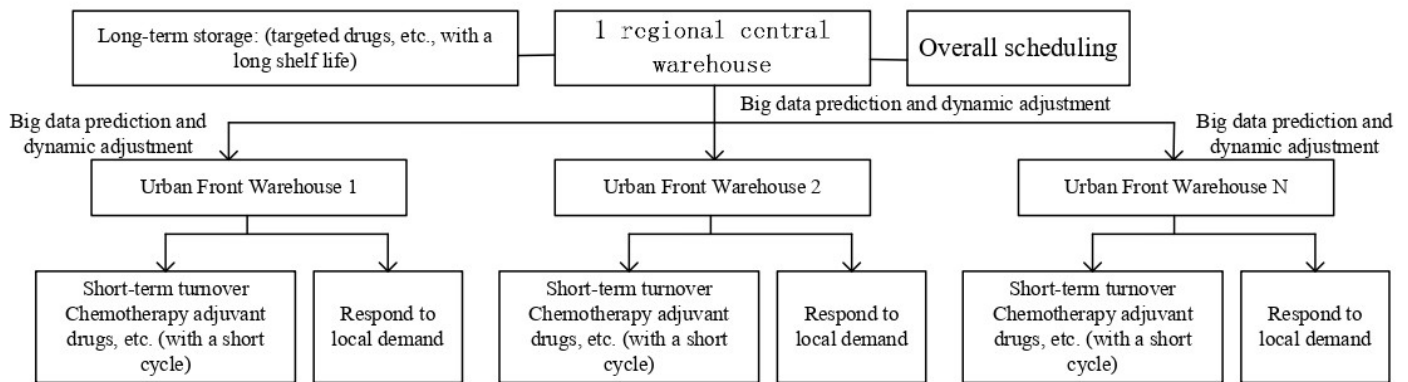


Figure 1. “1+N” distributed warehousing system.

After implementation: Huazhong Pharmaceutical Logistics implemented this framework in 2024, with an annual inventory turnover rate increase of 28.2% and a 57% decrease in the frequency of cross-regional emergency restocking.

4.2. Low-carbon transformation of facilities and equipment: technological innovation and energy efficiency improvement

(1) Refrigeration system upgrading

Traditional piston compressors can be replaced with magnetic-levitation variable-frequency compressors. Through precise variable-frequency regulation, the output power can be dynamically adjusted according to the real-time cooling demand of cold-storage facilities, thereby substantially reducing ineffective energy consumption. In addition, CO₂ transcritical refrigeration technology can be introduced. By using CO₂ as a natural refrigerant, this technology avoids the high greenhouse-effect risk caused by leakage of traditional refrigerants at the source, while also offering higher refrigeration efficiency under high-temperature conditions.

After the renovation of the self-operated warehouse in a South China oncology hospital, the COP of the refrigeration unit increased from 2.1 to 2.7, and the energy consumption of a single unit decreased by 22%. Precise layered temperature control enabled the temperature difference across the entire warehouse to remain below 0.3°C, thereby meeting the ±0.5°C storage standard required for anti-cancer drugs.

(2) Renewable energy integration

A “photovoltaic + energy storage” microgrid system can be established by installing high-efficiency solar panels over large areas of warehouse rooftops. This system converts solar energy into electricity, which can be directly supplied to refrigeration, lighting, and other warehousing systems, meeting approximately 30% of total electricity demand. Combined with differences between peak and off-peak electricity prices, energy storage batteries can store electricity during off-peak periods and release it during peak periods. This not only reduces dependence on the traditional power grid, but also decreases indirect carbon emissions caused by thermal power generation.

In Pilot Cold-chain Enterprise A, photovoltaic power generation met 30.2% of the warehouse's electricity demand. Peak-shaving energy storage further reduced indirect carbon emissions associated with thermal power generation by shifting electricity consumption away from peak periods.

(3) Application of green building standards

Warehousing facilities can adopt high-performance thermal insulation materials, such as new insulation panels with extremely low thermal conductivity. These materials can effectively block heat exchange between the inside and outside of cold-storage facilities, substantially reduce cooling loss, and lower the load on refrigeration systems. Intelligent daylighting systems can also be installed. Through the coordination of light sensors and automatic adjustment devices, artificial lighting can be flexibly regulated according to indoor light intensity, thereby increasing the utilisation of natural light to a higher level. This not only reduces lighting energy consumption, but also creates a more comfortable lighting environment for warehousing operations, implementing the concept of green and low-carbon development from the perspective of architectural design.

With the use of high-performance insulation panels and intelligent light-sensitive daylighting systems, cooling loss through the cold-storage envelope was reduced by 16%, while artificial lighting energy consumption decreased by 35%.

4.3. Operations management optimization: process reengineering and intelligent collaboration

(1) Low-carbon-oriented inventory management

Inventory strategies can be optimised based on the ABC classification method. For Class A drugs, which are characterised by high demand and high value, a “small-batch, high-frequency” replenishment approach can be adopted. By shortening the inventory cycle, this approach reduces energy consumption caused by long-term storage while also lowering the risk of inventory backlog.

For Class B drugs, which are commonly used medicines, inventory levels can be dynamically adjusted based on historical sales data and market forecasting models while maintaining a reasonable safety stock, thereby avoiding excessive reserves. For Class C drugs, which are low-demand drugs or special dosage forms, centralised storage in core warehouses can be adopted. Through large-scale management, this approach reduces equipment idleness and energy waste caused by dispersed storage. In this way, low-carbon management can be achieved in the inventory process through scientific classification. After pilot application, the backlog rate of slow-moving drugs decreased from 8.3% to 2.9%.

(2) Full-process carbon-footprint traceability

Blockchain technology can be used to record energy-consumption data at each stage of warehousing, including the operating duration and power consumption of refrigeration equipment, as well as the driving mileage and energy consumption of transport vehicles. Prior studies have highlighted the potential of blockchain to improve supply chain traceability, transparency, and sustainability-related accountability [27,28,30]. This enables the formation of an immutable full-chain carbon-footprint report, ensuring the authenticity and traceability of the data.

Through smart contracts, energy-consumption thresholds can be preset. Existing reviews of blockchain-based applications suggest that smart-contract mechanisms can strengthen automated monitoring and rule-based governance in complex supply chain systems, although implementation still requires attention to organisational readiness

and technical interoperability [26,29]. When energy consumption in a specific stage exceeds the threshold, the system automatically triggers an emission-reduction warning, promptly reminding managers to adjust equipment parameters or operational processes. This allows precise control of carbon emissions and provides data support for the continuous optimisation of low-carbon operations.

(3) Low-carbon coordination between warehousing and distribution

A “dock appointment system” can be adopted. Through a digital platform, the unloading time of refrigerated vehicles and the use of loading docks can be planned in advance, preventing vehicles from idling for long periods in unloading areas and reducing energy waste caused by the continuous operation of refrigeration systems.

Electric refrigerated vehicles with driving ranges suited to short-distance delivery needs can also be promoted to replace traditional fuel-powered refrigerated vehicles. This reduces exhaust emissions at the source. At the same time, delivery routes can be optimised to improve vehicle loading rates, further reducing transportation-related carbon emissions per unit of medicine and enabling the green transformation of the warehousing–distribution connection.

In one implementation case, Enterprise A in East China replaced 22 short-distance refrigerated vehicles, achieving an annual carbon-emission reduction of 17.6 tonnes in short-distance transportation.

5. Conclusion

This study, from an integrated perspective combining the “dual carbon” goals with the psychosocial needs of cancer patients, reveals the deeper humanistic value of optimising logistics and warehousing models for anti-cancer drugs. Based on pilot measurements and validation using clinical scales, the following conclusions are drawn.

(1) Benefits of warehousing network optimisation

In pilot enterprises where the “1+N” distributed warehousing and distribution model was implemented, full-chain carbon emissions were reduced by 12%–15%, and overall inventory turnover efficiency increased by 28%. The average regional delivery radius was controlled within 300 km, and patients’ waiting time for medication was significantly shortened.

(2) Empirical results on drug safety and patient psychology

Through warehousing transformation based on $\pm 0.5^{\circ}\text{C}$ precise temperature control and blockchain-based traceability, the average drug trust scale score in cooperating hospitals increased by 27%. Medication adherence, as measured by the MMAS, improved, while STAI anxiety scale scores decreased significantly.

(3) Improvement in family caregiving burden

Nearby warehousing and distribution reduced the costs incurred by patients travelling to other regions to purchase medication. Survey data show that the hidden economic burden of transportation, accommodation, and other expenses related to external drug purchasing among surveyed cancer families decreased by an average of 42%, effectively reducing family caregiving pressure.

Future research should focus on three directions with clinical and humanistic care value. In particular, future evaluation should incorporate patient-reported outcomes, as evidence from routine cancer treatment shows that systematic symptom monitoring can strengthen patient-centred care and clinical assessment [22]. First,

psychologically adaptive warehousing solutions under extreme climate conditions should be developed, with particular attention to assessing the impact of temperature-control fluctuations on the sense of safety among patients with advanced cancer. Second, a three-dimensional evaluation system integrating “low carbon, psychology, and efficiency” with patient-reported outcomes should be constructed, and machine learning should be used to identify the specific needs patterns of vulnerable populations. Third, a blockchain-based dual traceability mechanism for carbon data and psychological welfare should be established, providing a basis for oncology social workers to deliver precise support services.

When the green transformation of cold-chain logistics forms a positive interaction with the psychosocial needs of cancer patients, the goal of “full-chain zero carbon” will also become an important opportunity to improve the quality of humanistic care in healthcare. This is not only about environmental protection, but also a profound commitment to patients’ dignity in survival. It is recommended that clinical teams incorporate the choice of warehousing model into supportive care assessment and work with psychologists and social workers to develop a coordinated pathway linking logistics optimisation with psychological intervention.

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