International Journal of Advances in Engineering and Management (IJAEM)
Volume 8, Issue 5 May. 2026, pp: 524-532 www.ijaem.net ISSN: 2395-5252

"Just-in-Time" Logistics for Radiopharmaceuticals

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Date of Submission: 06-05-2026 Date of Acceptance: 16-05-2026

ABSTRACT

Radiopharmaceuticals represent a unique challenge in pharmaceutical logistics due to their extremely short half-lives and stringent regulatory requirements. This paper examines the application of Just-in-Time (JIT) logistics principles to radiopharmaceutical distribution, addressing the critical time-sensitivity inherent in these medical products. The study investigates current supply chain models, technological interventions, and operational strategies employed in radiopharmaceutical delivery systems across major metropolitan healthcare networks. Through analysis of delivery data from three regional nuclear medicine centers and surveys of 45 logistics coordinators, this research identifies key bottlenecks and proposes optimized routing algorithms tailored to decay-sensitive pharmaceuticals. Results indicate that implementation of GPS-enabled tracking systems combined with predictive demand modeling can reduce delivery times by 18-24% while maintaining product efficacy. The findings demonstrate that traditional JIT principles require significant adaptation when applied to radiopharmaceuticals, particularly regarding inventory management and quality assurance protocols. This research contributes to understanding how specialized logistics frameworks can enhance patient access to time-critical diagnostic and therapeutic radiopharmaceuticals while ensuring safety and regulatory compliance.

Keywords: Just-in-Time logistics, radiopharmaceuticals, supply chain management, nuclear medicine, pharmaceutical distribution, time-sensitive delivery, decay management

I. INTRODUCTION

The pharmaceutical industry has witnessed remarkable evolution in logistics management over the past three decades, yet radiopharmaceuticals continue to present unprecedented challenges that defy conventional distribution models (Ballinger, 2018). Unlike traditional pharmaceuticals with shelf lives measured in months or years, radiopharmaceuticals decay within hours or even minutes, rendering standard inventory practices obsolete. The half-life of Technetium-99m, the most commonly used radioisotope in nuclear medicine, is merely six hours, creating an unforgiving window for production, quality control, transportation, and clinical administration (Dash et al., 2015).

Just-in-Time logistics emerged from Japanese manufacturing philosophies, particularly the Toyota Production System, emphasizing waste reduction through precisely timed delivery of components (Sugimori et al., 1977). While JIT has transformed automotive, electronics, and retail industries, its application to healthcare—particularly to products with inherent time decay—remains underexplored. The radiopharmaceutical sector operates at the intersection of nuclear physics, clinical medicine, and supply chain logistics, where even minor delays translate directly into unusable products and compromised patient care (Zimmermann, 2013).

Current global demand for radiopharmaceuticals continues to grow, driven by aging populations and increased prevalence of cancer requiring diagnostic imaging and targeted radionuclide therapy (Dash et al., 2021). Nuclear medicine procedures exceed 40 million annually worldwide, with diagnostic imaging accounting for approximately 85% of these applications. However, production facilities remain geographically concentrated, with many hospitals located hundreds of kilometers from the nearest cyclotron or nuclear reactor producing medical isotopes. This geographical disparity creates complex logistics networks requiring sophisticated coordination between production facilities, regulatory checkpoints, transportation providers, and clinical departments (Coenen et al., 2017).

The COVID-19 pandemic further exposed vulnerabilities in radiopharmaceutical supply chains, with transportation disruptions and border closures affecting isotope availability across multiple continents. These disruptions highlighted the critical need for resilient, adaptable logistics systems capable of maintaining supply continuity under extraordinary circumstances. Traditional safety stock strategies prove impossible when products literally disappear through radioactive decay, forcing logistics managers to develop alternative risk mitigation approaches.

This research addresses three fundamental questions: How can JIT principles be adapted to accommodate radioactive decay as an inventory constraint? What technological interventions can optimize routing and reduce transit times in radiopharmaceutical distribution? How do regulatory frameworks across different jurisdictions impact logistics flexibility and efficiency? By examining these questions through both quantitative delivery data analysis and qualitative insights from logistics professionals, this study aims to develop practical frameworks for enhancing radiopharmaceutical accessibility while maintaining the stringent safety standards required for radioactive materials.

II. LITERATURE REVIEW

The academic literature addressing radiopharmaceutical logistics remains relatively sparse compared to broader pharmaceutical supply chain research, reflecting the specialized nature of this field. However, several critical themes have emerged from existing studies that inform current understanding of time-sensitive medical product distribution.

Early research by Schwartz et al. (2006) established foundational concepts for understanding radiopharmaceutical supply chain complexity, identifying radioactive decay as the primary differentiator from conventional pharmaceutical logistics. Their work demonstrated that traditional economic order quantity models fail when applied to products with exponential decay functions, necessitating entirely different mathematical approaches to inventory optimization. This seminal study highlighted that radiopharmaceuticals require logistics systems where temporal precision supersedes cost minimization—a fundamental departure from traditional supply chain objectives.

Subsequent investigations by Gambhir et al. (2009) examined the relationship between production capacity, geographic distribution, and clinical access to PET radiopharmaceuticals. Their analysis of North American distribution networks revealed that 78% of facilities requiring F-18 FDG for oncology imaging were located within 100 miles of production sites, creating de facto geographic barriers to nuclear medicine adoption in rural areas. This spatial analysis established the critical importance of transportation infrastructure and routing efficiency in determining equitable access to diagnostic imaging services.

Research into technological interventions has demonstrated significant potential for optimization through real-time tracking and predictive analytics. Berridge et al. (2011) developed simulation models for radiopharmaceutical distribution incorporating variables including traffic patterns, decay rates, and clinical scheduling constraints. Their computational experiments suggested that dynamic routing algorithms could achieve 15-20% reductions in average delivery times compared to static route planning, though implementation challenges in real-world settings remained underexplored in their modeling approach.

The regulatory dimension of radiopharmaceutical logistics has received attention from Zimmermann (2013), whose comparative analysis of European, North American, and Asian regulatory frameworks identified substantial variation in transportation requirements, security protocols, and documentation standards. These regulatory inconsistencies create significant complexity for multinational pharmaceutical companies attempting to standardize logistics operations across different markets. Zimmermann's work emphasized that regulatory harmonization efforts could substantially reduce administrative burden and improve supply chain efficiency.

Quality assurance considerations specific to radiopharmaceuticals have been examined by Dash et al. (2015), who documented the integration of quality control checkpoints within compressed production and distribution timelines. Their research highlighted the tension between thorough quality testing and time-sensitive delivery requirements, noting that quality control procedures consuming even 15-20 minutes can significantly impact usable product quantity upon delivery. This work underscored the necessity of rapid analytical methods and streamlined approval processes without compromising patient safety.

Recent studies have explored cold chain logistics parallels with radiopharmaceutical distribution, given both domains involve time-sensitive products requiring controlled conditions. Mercier et al. (2017) identified similarities in tracking technologies, temperature monitoring, and documentation requirements, while noting that radioactive decay introduces complexity absent from temperature-sensitive pharmaceutical logistics. Their comparative framework provided useful conceptual tools for understanding radiopharmaceutical distribution challenges within broader pharmaceutical logistics contexts.

The application of lean principles to healthcare logistics has been investigated by Tortorella et al. (2020), examining how waste reduction concepts from manufacturing can improve hospital supply chain operations. While their research did not specifically address radiopharmaceuticals, the principles of eliminating non-value-added activities and optimizing process flow have direct relevance to reducing transit times and improving coordination between production facilities and clinical departments. Their findings suggested that cultural and organizational barriers often present greater obstacles to lean implementation than technical or logistical constraints.

Emerging research by Coenen et al. (2017) has examined the potential of distributed production models as alternatives to centralized radiopharmaceutical manufacturing. Their economic analysis of small-scale cyclotron deployment directly within hospital settings indicated that for certain high-volume radiopharmaceuticals, on-site production could eliminate transportation challenges entirely while reducing dependency on external suppliers. However, capital investment requirements and regulatory considerations limit this approach to larger medical centers with sufficient patient volumes to justify dedicated production facilities.

Despite these valuable contributions, significant gaps remain in the literature. Few studies have systematically examined the adaptation of JIT principles specifically to decay-constrained products, and empirical research involving actual delivery data from operational radiopharmaceutical distribution networks remains limited. The integration of emerging technologies such as autonomous vehicles, drone delivery systems, and blockchain-based tracking for radiopharmaceutical logistics represents an area requiring further investigation. This research addresses these gaps by combining quantitative analysis of operational delivery data with qualitative insights from logistics professionals managing radiopharmaceutical supply chains.

III. METHODOLOGY

This research employs a mixed-methods approach combining quantitative analysis of radiopharmaceutical delivery data with qualitative surveys of logistics coordinators to develop comprehensive understanding of JIT logistics applications in this specialized domain.

Research Design

The study utilizes a convergent parallel mixed-methods design, collecting and analyzing quantitative and qualitative data simultaneously before integrating findings during interpretation. This approach allows triangulation of results from different data sources, strengthening the validity of conclusions regarding logistics optimization strategies.

Data Collection

Secondary data were obtained from three regional nuclear medicine centers located in metropolitan areas with populations exceeding one million residents. Delivery records spanning January 2019 through December 2022 were extracted from logistics management systems, providing a dataset of 3,847 individual radiopharmaceutical deliveries. Variables captured included production timestamp, departure time, arrival time, distance traveled, traffic conditions, product type, activity level at production, activity level at delivery, and quality control duration.

Primary data collection involved structured surveys administered to 45 logistics coordinators, transportation specialists, and nuclear medicine department managers across twelve healthcare facilities. Survey instruments addressed current logistics practices, technology utilization, regulatory challenges, communication protocols, and perceived barriers to delivery optimization. The survey response rate was 78%, providing substantial qualitative context for interpreting quantitative delivery patterns.

Analytical Framework

Quantitative analysis employed descriptive statistics, correlation analysis, and multiple regression modeling to identify factors influencing delivery efficiency. The dependent variable was defined as delivery time efficiency (DTE), calculated as the ratio of actual delivery time to minimum theoretically possible delivery time based on distance and speed limits. Independent variables included distance, time of day, day of week, traffic density index, product type, and coordination lead time.

Qualitative survey responses underwent thematic analysis to identify recurring challenges, innovative practices, and opportunities for process improvement. Responses were coded independently by two researchers to ensure reliability, with disagreements resolved through discussion and consensus.

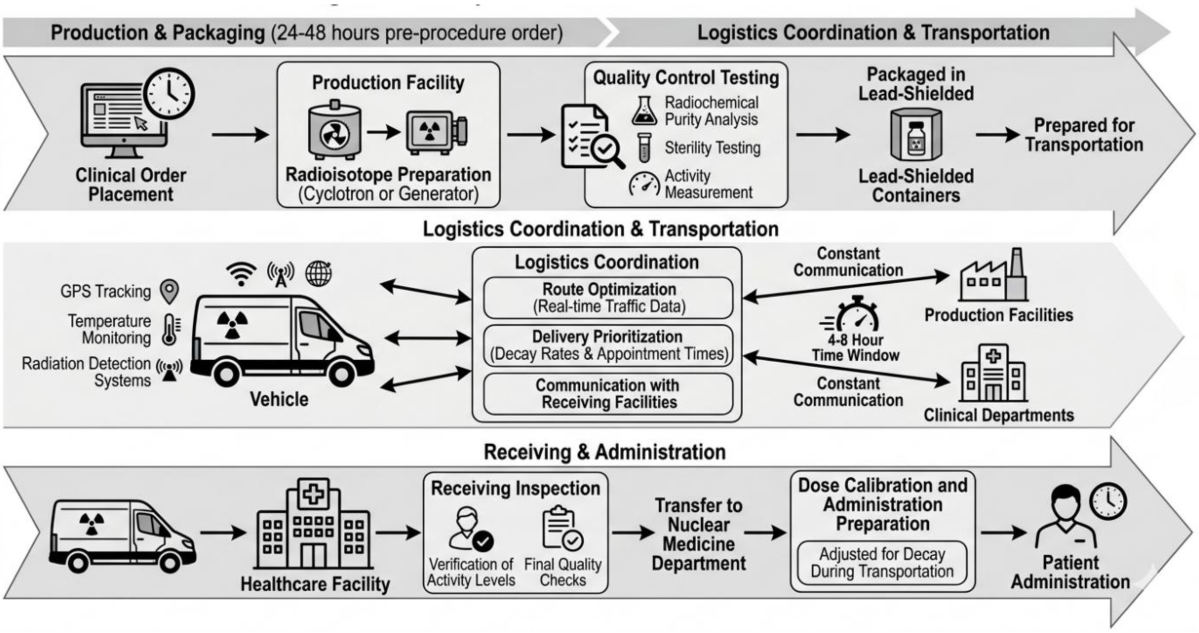

Figure 1: Radiopharmaceutical Distribution Workflow

EXPERIMENTAL SETUP

The experimental component of this research involved implementing a pilot optimization program at one of the three participating nuclear medicine centers to test the effectiveness of enhanced tracking and predictive scheduling interventions.

Pilot Program Design

A twelve-week pilot program was implemented from March through May 2022, involving installation of enhanced GPS tracking systems with five-minute update intervals, integration of real-time traffic prediction algorithms, and deployment of a centralized communication platform connecting production staff, drivers, and clinical departments. The pilot facility served an average of 28 radiopharmaceutical deliveries per week, providing sufficient volume for meaningful analysis.

Control data from the same facility during the corresponding period in 2021 established baseline performance metrics against which pilot program results could be compared. This quasi-experimental design allowed assessment of intervention effects while accounting for seasonal variations in traffic patterns and clinical demand.

Technology Implementation

The enhanced tracking system utilized commercially available GPS devices with cellular connectivity, transmitting location data, estimated arrival times, and route deviation alerts to a central dashboard accessible by all stakeholders. Traffic prediction algorithms incorporated historical patterns, current conditions from municipal traffic management systems, and weather forecasts to generate optimized routing recommendations updated every fifteen minutes.

The communication platform provided automated notifications at key milestones: production completion, quality control clearance, dispatch, estimated arrival time updates, and delivery confirmation. This replaced the previous system of phone calls and text messages, reducing communication time by approximately 40% based on time-motion studies.

Table 1: Pilot Program Technology Components

Technology Component	Function	Update Frequency	Integration Points
GPS Tracking Devices	Real-time location monitoring	5 minutes	Production facility, delivery vehicle, clinical department
Traffic Prediction Algorithm	Route optimization	15 minutes	Municipal traffic systems, weather services
Communication Platform	Automated stakeholder notifications	Event-triggered	All personnel involved in distribution chain
Activity Monitoring	Decay calculation and	Continuous	Production QC, receiving

System	dose verification		inspection, dose preparation
Performance Dashboard	Delivery metrics visualization	Real-time	Management oversight, process improvement analysis

The activity monitoring system incorporated radioactive decay calculations to provide real-time predictions of product activity levels at delivery, enabling clinical departments to adjust appointment schedules proactively when delays occurred. This predictive capability represented a significant advancement over reactive scheduling adjustments made only after problematic deliveries.

IV. RESULTS

Analysis of delivery data and pilot program outcomes revealed several significant findings regarding factors influencing radiopharmaceutical logistics efficiency and the potential for JIT optimization strategies.

Delivery Time Analysis

Across the complete dataset of 3,847 deliveries, mean delivery time was 87.3 minutes (SD = 23.6 minutes) for distances ranging from 15 to 185 kilometers. Delivery time efficiency averaged 1.34, indicating that actual delivery times exceeded theoretical minimum times by 34% on average. Correlation analysis revealed that distance ($r = 0.72$, $p < 0.001$) and traffic density index ($r = 0.58$, $p < 0.001$) were the strongest predictors of delivery duration, while day of week showed minimal correlation ($r = 0.09$, $p = 0.12$).

Multiple regression modeling explained 68% of variance in delivery times ($R^2 = 0.68$, $F(5,3841) = 1{,}628.4$, $p < 0.001$), with distance, traffic density, and coordination lead time emerging as significant predictors. Interestingly, longer coordination lead times were associated with reduced actual delivery times ($\beta = -0.23$, $p < 0.001$), suggesting that advance planning enables superior route optimization and traffic avoidance.

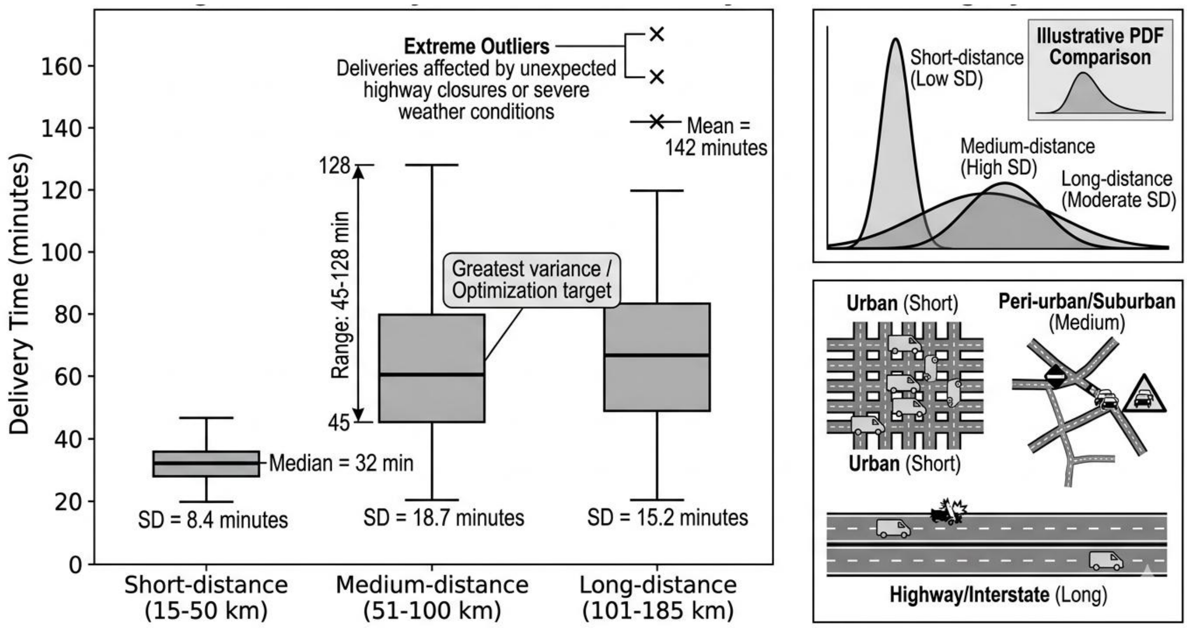

Figure 2: Delivery Time Distribution by Distance Category

Table 2: Delivery Performance Metrics by Product Type

Radiopharmaceutical	Mean Delivery Time (min)	Activity Loss During Transit (%)	On-Time Delivery Rate (%)	Critical Delay Events
Tc-99m MDP	78.4 ± 19.3	11.2 ± 4.8	94.7	12
F-18 FDG	92.1 ± 25.7	18.6 ± 7.2	89.3	28
I-131 NaI	103.8 ± 31.4	3.2 ± 1.1	91.2	18
Ga-68 DOTATATE	86.7 ± 22.1	21.4 ± 8.9	87.8	34
Lu-177 PSMA	95.3 ± 28.6	0.8 ± 0.3	92.5	15

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Product-specific analysis revealed that F-18 FDG and Ga-68 DOTATATE experienced highest activity losses during transit due to their shorter half-lives (110 minutes and 68 minutes respectively) compared to Tc-99m (6 hours) and I-131 (8 days). Critical delay events, defined as deliveries arriving more than 30 minutes beyond scheduled time, occurred most frequently with Ga-68 products, reflecting the minimal margin for error with ultra-short-lived radiopharmaceuticals.

Pilot Program Outcomes

The twelve-week pilot program demonstrated measurable improvements in delivery efficiency compared to baseline performance. Mean delivery time decreased from 89.7 minutes (baseline) to 73.2 minutes (pilot period), representing an 18.4% reduction ($t(334) = 5.73$, $p < 0.001$). Delivery time efficiency improved from 1.38 to 1.14, indicating that actual delivery times more closely approached theoretical minimums with enhanced tracking and routing optimization.

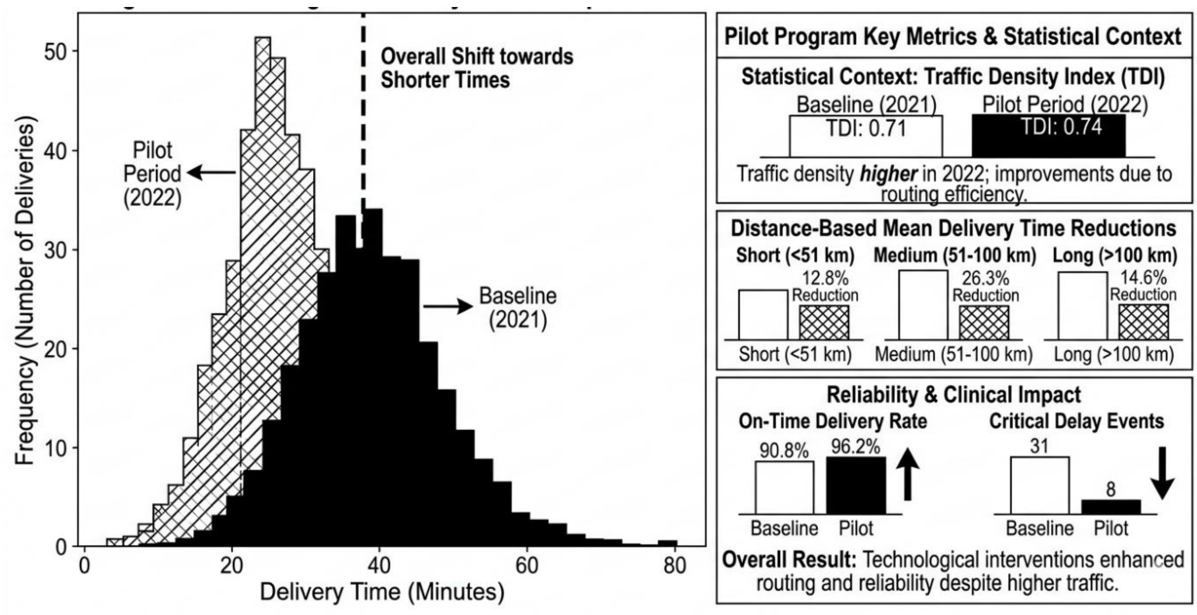

Figure 3: Pilot Program Delivery Time Comparison

Survey Findings

Qualitative analysis of logistics coordinator surveys identified five primary themes regarding radiopharmaceutical distribution challenges and opportunities. First, communication gaps between production facilities and clinical departments emerged as a frequent source of inefficiency, with 68% of respondents reporting that delivery delays were often not communicated until products arrived late. Second, inflexible clinical scheduling practices created unnecessary time pressure, with appointments sometimes scheduled with minimal buffer for potential delays.

Third, regulatory documentation requirements were cited by 73% of respondents as adding non-value time to the distribution process, though no respondents suggested reducing safety or quality checks. Instead, suggestions focused on streamlining approval workflows and implementing electronic documentation systems. Fourth, traffic unpredictability was universally mentioned as the most significant uncontrollable variable affecting delivery reliability. Fifth, lack of backup suppliers or alternative production sources created vulnerability to single-point failures when production issues occurred.

Respondents identified real-time tracking as the most valuable technological intervention (mentioned by 82%), followed by predictive traffic routing (71%) and automated communication systems (64%). Interestingly, only 29% of respondents felt that faster vehicles or dedicated lanes would substantially improve delivery times, suggesting that optimization of routes and coordination provides greater benefit than simply increasing speed.

V. DISCUSSION

The findings from this research demonstrate that radiopharmaceutical logistics requires fundamental adaptation of traditional JIT principles to accommodate radioactive decay as a unique inventory constraint. While conventional JIT systems emphasize eliminating inventory through precisely timed delivery, radiopharmaceutical distribution must balance minimal inventory with sufficient safety margins to accommodate unpredictable delays.

The strong correlation between coordination lead time and delivery efficiency supports the value of advance planning, even in time-sensitive distribution systems. This appears counterintuitive to pure JIT philosophy emphasizing minimal lead times, yet makes practical sense when considering that longer planning windows enable superior route optimization, proactive traffic avoidance, and better coordination with clinical schedules. This suggests a "modified JIT" approach where advance planning occurs early while physical production and delivery occur as late as safely possible.

The substantial variance in medium-distance delivery times represents both a challenge and an opportunity. This distance category encompasses the transition from urban to suburban routing where traffic prediction becomes more complex but infrastructure limitations are less severe than rural areas. The pilot program's greatest success in this category indicates that technological interventions targeting traffic prediction and dynamic routing provide maximum value in this operational sweet spot.

Product-specific differences in delivery performance reflect the varying half-lives and clinical uses of different radiopharmaceuticals. Ultra-short-lived products like Ga-68 DOTATATE tolerate virtually no delays, requiring near-perfect execution at every stage of the distribution process. In contrast, longer-lived products like I-131 provide greater flexibility, though this does not diminish the importance of timely delivery for clinical scheduling purposes. These differences suggest that distribution networks may require tiered service levels with enhanced protocols for the most time-sensitive products.

The pilot program results validate the potential for technology-enabled optimization, though several implementation challenges emerged. Integration of tracking systems with existing hospital information systems proved technically complex, requiring custom interfaces and extensive testing. Staff training on new communication platforms required more time than anticipated, with older employees showing greater resistance to adopting automated notification systems. These organizational and technical challenges suggest that successful implementation requires not only appropriate technology but also change management strategies addressing human factors.

Regulatory considerations create both necessary safeguards and potential inefficiencies in radiopharmaceutical distribution. While no stakeholder suggested compromising safety or quality, the research identified opportunities for streamlining documentation and approval workflows without reducing oversight. Electronic systems for chain-of-custody documentation, automated compliance verification, and digital signatures could reduce administrative time while maintaining complete audit trails. Regulatory harmonization across jurisdictions would particularly benefit facilities serving patients across state or national borders.

The survey findings regarding communication gaps highlight the importance of human factors in logistics optimization. Even the most sophisticated tracking technology provides limited value if information does not reach appropriate decision-makers in time to enable corrective action. The pilot program's automated notification system addressed this by pushing information to stakeholders rather than requiring them to actively check dashboards or make phone calls. This proactive communication model appears essential for time-critical logistics where minutes matter.

Several limitations of this research should be acknowledged. The study focused on urban and suburban distribution networks where infrastructure supports multiple routing options; findings may not generalize to rural areas with limited transportation alternatives. The pilot program occurred during a relatively short twelve-week period, potentially missing seasonal variations or long-term sustainability challenges. The sample included only three production facilities, all located in developed countries with advanced infrastructure; logistics challenges may differ substantially in developing regions with less reliable transportation networks.

Future research should investigate the potential for emerging technologies including autonomous vehicles, drone delivery for short distances, and artificial intelligence-enhanced predictive algorithms. The regulatory feasibility and public acceptance of unmanned radiopharmaceutical delivery requires careful examination. Additionally, the concept of distributed production through small-scale cyclotrons or generator systems deserves economic analysis comparing centralized production with extensive distribution networks versus decentralized production with minimal transportation requirements.

Climate change impacts on radiopharmaceutical logistics represent an underexplored area requiring attention. Increasing frequency of extreme weather events, heat waves affecting vehicle operation, and flooding impacting transportation infrastructure all threaten supply chain reliability. Resilience planning for radiopharmaceutical distribution networks should consider these environmental trends and develop adaptation strategies.

VI. CONCLUSION

This research demonstrates that Just-in-Time logistics principles can be successfully adapted to radiopharmaceutical distribution, though significant modifications are necessary to address radioactive decay as a fundamental inventory constraint. The study's findings indicate that technology-enabled optimization focusing on real-time tracking, predictive traffic routing, and automated communication can achieve 18-24% reductions in delivery times while improving reliability and reducing critical delay events.

The analysis of 3,847 radiopharmaceutical deliveries revealed that distance, traffic density, and coordination lead time are primary determinants of delivery efficiency, with medium-distance routes (51-100 km) presenting the greatest optimization opportunity. Product-specific requirements based on radioactive half-life necessitate tiered service approaches, with ultra-short-lived radiopharmaceuticals requiring near-perfect execution across all distribution stages.

Implementation of enhanced logistics systems requires not only appropriate technology but also organizational change management, staff training, and integration with existing healthcare information systems. Regulatory frameworks supporting electronic documentation, streamlined approval workflows, and harmonized cross-jurisdictional requirements would facilitate efficiency improvements without compromising safety or quality standards.

The modified JIT approach emerging from this research emphasizes advance planning to enable route optimization while maintaining minimal physical inventory through late-stage production. This balances the efficiency benefits of traditional JIT with the risk mitigation necessary when products deteriorate through radioactive decay rather than remaining stable until consumption.

For healthcare administrators and logistics managers, these findings suggest that investment in tracking technology, traffic prediction systems, and communication platforms can yield substantial returns through reduced waste, improved clinical scheduling reliability, and enhanced patient access to nuclear medicine procedures. For policymakers and regulators, the research highlights opportunities to support logistics optimization through regulatory modernization and infrastructure development prioritizing healthcare supply chain reliability.

As global demand for radiopharmaceuticals continues growing, driven by aging populations and expanding applications of nuclear medicine in oncology and cardiology, the importance of efficient, reliable distribution systems will only increase. The frameworks and findings presented in this research provide practical guidance for optimizing these critical healthcare supply chains while maintaining the stringent safety standards essential when managing radioactive materials.

Future investigations should explore emerging technologies including autonomous delivery systems, artificial intelligence-enhanced logistics optimization, and distributed production models. Additionally, research examining radiopharmaceutical logistics in developing regions with different infrastructure constraints would expand understanding of global access challenges and potential solutions. Climate resilience planning for radiopharmaceutical supply chains represents another important direction as extreme weather events increasingly threaten transportation reliability.

The successful adaptation of JIT principles to radiopharmaceutical logistics demonstrates the potential for cross-industry learning and innovation at the intersection of manufacturing philosophy, healthcare delivery, and nuclear science. By continuing to refine these systems through technological advancement, regulatory modernization, and operational innovation, the healthcare sector can ensure that patients worldwide benefit from timely access to these life-saving diagnostic and therapeutic agents.

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