Vol. 09, No. 02, July 2025, pp. 123-133

INTERNATIONAL JOURNAL OF INNOVATION IN ENTERPRISE SYSTEM

Journal homepage: https://ijies.sie.telkomuniversity.ac.id
e-ISSN: 2580-3050, DOI: https://doi.org/10.25124/ijies.v9i02.9739

Applying EOQ with Sustainability Metrics in Vaccine Packaging Management

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ARTICLE INFO

Article history:
Received 03 August 2025
Accepted 26 October 2025
Published 05 November 2025

ABSTRACT IN ENGLISH

Sustainable supply chain management (SSCM) is crucial in vaccine distribution, where poor packaging inventory control lead to excessive waste and carbon emissions. This study applies the classical Economic Order Quantity (EOQ) model to optimize vaccine packaging inventory and evaluates its outcomes using sustainability indicators (packaging waste, emergency shipments, and CO_2e). A case study at a major Indonesian vaccine manufacturer shows how EOQ-based planning, followed by sustainability impact assessment, improves operational efficiency while reducing environmental burdens. Rather than embedding environmental variables inside the EOQ formula, sustainability is operationalized as a downstream impact-assessment layer that quantifies the consequences of EOQ decisions. Using historical operational data and standard emission factors, results indicate an estimated ~50% reduction in packaging surplus and ~15% reduction in cold-chain emissions annually when compared with prior practices. These findings position EOQ as a practical decision-support tool that aligns inventory control with SSCM goals in cold-chain logistics.

Keywords:
Economic Order Quantity;
Sustainable Supply Chain;
Vaccine Packaging;
Inventory; Green Logistics;
Cold Chain Logistics

1. INTRODUCTION

Ensuring the availability and timely delivery of vaccines is a critical challenge in global public health. As vaccines must be handled under precise conditions and delivered rapidly to meet immunization targets, supply chain efficiency becomes paramount. While significant advances have been made in vaccine production and cold chain logistics, one area that remains under-optimized is packaging inventory management. Inadequate planning of packaging stock can lead to overordering, shortages, and costly emergency shipments, consequently generating unnecessary waste and carbon emissions. This study addresses this operational and environmental issue by exploring how the classical Economic Order Quantity (EOQ) model can be integrated with Sustainable Supply Chain Management (SSCM) principles to improve vaccine packaging inventory practices. The aim is to design a conceptual framework that connects cost-based inventory planning with environmental sustainability metrics, thus bridging two typically isolated areas in supply chain studies.

Vaccines are complex biological products that stimulate the immune system to prevent infectious diseases. Their global deployment has significantly reduced the prevalence of diseases such as COVID-19, polio, and measles [1]. Given their temperature sensitivity, vaccines are transported via tightly controlled cold chains, typically requiring 2–8 °C or −20 °C conditions [2]. However, maintaining this integrity is not solely dependent on the cold chain infrastructure—it also relies heavily on the availability of suitable packaging materials such as insulated containers, coolant packs, dry ice, and temperature loggers. Poor forecasting and irregular replenishment of these materials can result in last-minute procurement, stockouts, or surplus waste, particularly in low- and middle-income countries [3-6]. Studies have shown that in many developing contexts, up to 50% of packaging shipments may arrive late due to inadequate safety stock and inconsistent replenishment schedules, undermining target service levels [7, 8].

In recent years, the global pharmaceutical industry has come under increasing pressure to align its operations with sustainability goals, particularly in support of the United Nations Sustainable Development Goals (SDGs), such as SDG 3 (Good Health and Well-being), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production). Regulatory bodies, international donors, and procurement agencies are now demanding not only timely delivery and cost efficiency, but also measurable environmental responsibility in supply chain practices. As part of this shift, manufacturers are expected to reduce single-use plastics, minimize logistics emissions, and implement circular economy principles in their packaging and distribution strategies. However, many current inventory planning tools remain disconnected from these sustainability priorities, resulting in missed opportunities to optimize both operational and environmental outcomes in tandem [9, 10]. This study addresses this disconnect by embedding sustainability considerations into a classical inventory model, ensuring that packaging logistics contribute meaningfully to long-term health and climate objectives. From a public-health perspective, reducing stockouts and emergency shipments helps improve vaccine availability and the continuity of immunization services, thereby contributing to broader health system resilience.

Inventory control models such as Just-In-Time (JIT), Vendor-Managed Inventory (VMI), and EOQ are widely used to manage healthcare logistics efficiently [11-13]. The EOQ model, first developed by Harris (1913), remains a fundamental approach for determining optimal order quantities to minimize total inventory costs [14]. By calculating the balance point between ordering costs and holding costs, EOQ provides a systematic method for stock planning. When supported by real-time monitoring and predictive analytics, EOQ can reduce stockouts and excess stock while ensuring service levels [15, 16].

However, despite its wide use for cost optimization, existing EOQ models and implementations have rarely incorporated environmental indicators such as carbon emissions or packaging waste. As Seuring and Müller [17] argue, integrating sustainability into supply chain management requires balancing economic, environmental, and social aspects, the triple bottom line. Yet, most operational inventory models still focus narrowly on financial efficiency and exclude key environmental metrics such as carbon footprint, material waste, or potential for reuse [18-20]. In vaccine supply chains, this omission can be significant because poorly planned packaging stock not only increases costs but also drives up greenhouse gas emissions through unplanned urgent shipments and generates avoidable solid waste when materials expire unused [21, 22].

This study aims to fill this research gap by developing a framework that integrates EOQ with sustainability indicators in a vaccine packaging context—something that is currently lacking in both the inventory management and SSCM literature. The novelty of this paper lies in its operational focus: it does not merely suggest theoretical sustainability alignment but demonstrates how classical EOQ calculations can be adapted to support sustainable decision-making using real-world data. A case study from a vaccine manufacturer is used to evaluate the impact of the proposed approach, showing potential reductions in packaging surplus by up to 50% and transport-related emissions by up to 15%.

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By clarifying this link, the study contributes to the growing body of literature on Sustainable Supply Chain Management. It responds to calls from scholars such as Sarkis [23] and Geissdoerfer et al. [24] for more practical, data-driven tools that integrate sustainability into day-to-day operational decisions. The results of this study are expected to support vaccine manufacturers, policymakers, and logistics planners in improving inventory performance while reducing environmental impacts, especially in cold chain operations where precision and sustainability must go hand in hand.

The objective of this study is to apply the classical EOQ model for vaccine packaging management and evaluate its outcomes using sustainability indicators so that cost-efficient decisions can be explicitly linked to environmental performance. Guided by this objective, we address the following questions: (RQ1) How does EOQ-based planning change ordering patterns, holding costs, and emergency shipments for vaccine packaging? (RQ2) What sustainability effects (e.g., packaging waste and CO_2e) are observed when EOQ outcomes are evaluated with standard indicators? (RQ3) How can these insights be formalized into a practical framework that supports continuous monitoring and improvement in cold-chain logistics? By clarifying that sustainability is assessed (not embedded as variables in the EOQ formula), the study extends EOQ's role from cost minimization to a decision-support bridge between operational planning and SSCM objectives.

The remainder of this paper consists of three sections. Section 2 describes the research methods, including the rationale for applying the EOQ model, the data collection process, and how sustainability indicators were incorporated to ensure validity and reliability. Section 3 presents the results and discussion, highlighting the main findings and explaining how these answer the research objectives. Section 4 concludes the paper with a synthesis of key points, practical implications, and suggestions for future research.

2. RESEARCH METHOD

2.1. Research Design and Rationale

This research adopts a quantitative case study design to evaluate the potential of integrating the EOQ model with sustainability performance indicators in a vaccine supply chain setting. A case study approach enables an in-depth examination of real-world inventory management challenges, offering insights grounded in actual operational contexts. The methodology sequence follows five main stages: (1) Problem Identification, (2) Data Collection, (3) EOQ Calculation, (4) Estimation of Sustainability Impact, and (5) Framework Development, as shown in Figure 1. The selection of EOQ as the core tool is based on its longstanding utility in optimizing inventory costs and order planning efficiency [3, 4]. Most classical EOQ implementations focus solely on economic efficiency, overlooking environmental externalities. This study fills that gap by connecting EOQ outputs with waste and emission metrics, contributing to the operationalization of SSCM principles [5, 6]. However, instead of embedding sustainability variables inside the EOQ formula, the model's results are later evaluated using sustainability indicators such as packaging waste reduction, reduced emergency shipments, and CO_2-emission savings. This approach positions sustainability as an impact-assessment layer that complements EOQ cost optimization in real-world vaccine operations.

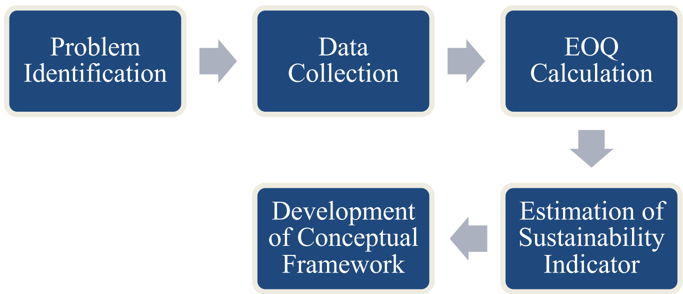

Figure 1 - Research methodology

2.2. Step 1: Problem Identification

The first step aimed to identify key pain points in the current vaccine packaging inventory system. A series of semi-structured interviews were conducted with staff in the logistics, warehouse, and procurement departments of a major vaccine manufacturer. The purpose was to uncover systemic issues that affect order planning and stock availability. Common problems identified included frequent stockouts, expired materials due to overstocking, and high emergency-shipment frequency, causing excessive costs and emissions. These findings established the baseline for subsequent EOQ analysis and sustainability evaluation.

2.3. Step 2: Data Collection and Preparation

2.3.1. Primary Data

Primary data were gathered via semi-structured interviews with personnel directly involved in inventory control, procurement, and packaging logistics. These interviews yielded valuable qualitative inputs on operational routines, bottlenecks, and historical ordering behavior. Key topics included:

- Average monthly demand and seasonal variations.
- Lead time variability and typical supplier delays.
- Packaging disposal frequency and waste causes.
- Experience with urgent procurement and associated logistics issues.

In total, six participants were interviewed: one representative each from the logistics, warehouse, and procurement divisions, and three representatives from the distribution division. This uneven distribution reflects access limitations during the data-collection phase; the company assigned only one contact per department, except for distribution, where three participants were available. The distribution division received greater emphasis because most operational problems, such as emergency shipments and fluctuating packaging demand, originated there.

2.3.2. Secondary Data

Quantitative data were extracted from internal company records, including:

- Inventory movement reports (January–October 2024).
- Purchase order histories and supplier lead time logs.
- Disposal logs for expired packaging materials.
- Cold chain transport logs and emission estimates.

Environmental impacts were quantified using DEFRA (2023) emission-conversion factors to translate shipping patterns into CO_2-equivalent indicators [7].

2.4. Step 3: EOQ Model Formulation

The core of the analysis involved applying the EOQ formula to optimize order quantities for each packaging item. The classical EOQ model was implemented using Equations (1) and (2):

$$EOQ = \sqrt{\frac{2 \times D \times S}{H}} \tag{1}$$

$$F = \frac{D}{EOQ} \tag{2}$$

Where D represents annual demand, S is the ordering cost per order, H is for holding cost per unit per year, and F represents the frequency of orders per year. Because the assumptions of the classical EOQ (constant demand and lead time) are rarely met in real operations, we incorporated adjustments using historical demand variability and supplier lead-time data. Safety stock and reorder point (ROP) were therefore included to buffer against uncertainty. Equations (3) and (4) are used to calculate safety stock and reorder points, respectively.

$$SafetyStock = \sigma \times Z \times \sqrt{LT} \tag{3}$$

$$\text{ReorderPoint} = \left(D \times LT\right) + SafetyStock \tag{4}$$

These modifications allow EOQ results to remain applicable under dynamic vaccine-packaging conditions. These calculations allowed for setting optimal inventory parameters that balance cost efficiency and supply continuity. The modeling was conducted in Microsoft Excel and validated using past demand data.

2.5. Step 4: Estimation of Sustainability Impact

After determining EOQ-based order quantities, the outcomes were evaluated through sustainability indicators:

- Packaging waste reduction (kg of used materials avoided),
- Emergency shipments avoided (number and percentage reduction), and
- Estimated CO_2-equivalent emissions reduction (based on DEFRA 2023 factors).

For example, reductions in packaging surplus were translated into kilograms of waste avoided using average unit weights. Emergency shipments avoided were calculated using historical transport data, and then multiplied by emission factors (e.g., 0.5–0.7 tons CO_2e per shipment) [8]. These results provided evidence for the environmental co-benefits of improved inventory control. This stage functions as an evaluation layer rather than a mathematical integration, confirming that EOQ-driven efficiency contributes indirectly to sustainability outcomes.

2.6. Step 5: Framework Development

The final step developed a conceptual framework linking EOQ outputs with sustainability evaluation and continuous monitoring. Validation combined data triangulation (interviews × operational logs × emission data), stakeholder review sessions with logistics and distribution managers, and cross-checking of historical cost trends. This stakeholder-based validation ensures that the proposed framework is both realistic and replicable. Furthermore, this approach aligns with previous recommendations in inventory-model validation studies emphasizing stakeholder engagement and triangulation across multiple data sources [25, 26].

This practical tool serves as a roadmap for integrating SSCM metrics into operational-level planning. The framework is shown in Figure 2 and is proposed as a scalable model for pharmaceutical and cold chain logistics sectors.

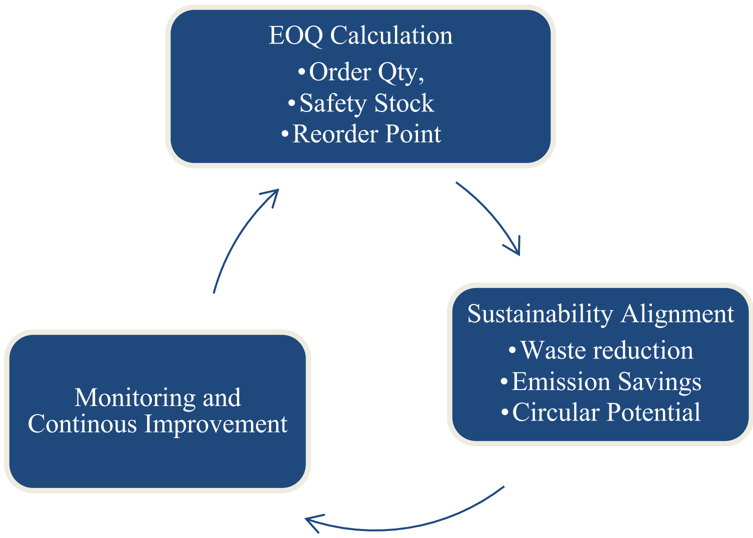

Figure 2 - Proposed conceptual framework integrating EOQ with sustainability alignment and continuous monitoring

3. RESULT AND DISCUSSION

3.1. EOQ Calculation Results and Interpretation

The EOQ model was applied to determine optimal order quantities and frequencies for 16 types of vaccine packaging used by the manufacturer. Table 1 summarizes the EOQ values and the resulting order frequencies. The results indicate that EOQ-based planning creates a more stable and cost-efficient ordering pattern compared to ad-hoc procurement practices previously used by the company.

Table 1 - EOQ Purchase Quantity and Frequency.

Vaccine Packaging Name	D	EOQ	F
Polyurethane Box White No. 1	17.427	2.151	9
Polyurethane Box White No. 2	558	144	4
Vaccine & Serum Carton No. 2	1.765	440	5
GG Styrofoam Box (Local)	3.567	833	5
Cool Pack (Red, White, Blue)	427.184	16.882	26
Dry Ice	17.913	1.816	10
Freeze Alert	6.066	498	13
Vax Alert Type A.B	5.893	436	14
Vax Alert Type C	604	109	6
Logtag	1.235	189	7
Logtag WHO Type A.B	5.893	335	14
Logtag WHO Type C	10	3	4
Logtag Elitech (Log ET1)	843	123	7
Plastic	7.718	1.491	6
Bubble Wrap	36.570	3.659	10
Styrofoam Sheet	26.911	4.316	7
Label Roll (Sticker)	72.223	6.431	12

For instance, the Cool Pack, with over 400,000 units of annual demand, now requires 26 purchasing cycles per year under EOQ-based planning. This helps minimize total inventory costs, as holding and ordering costs are better balanced. These findings support previous research on the benefits of EOQ in healthcare logistics, such as the works by Uthayakumar and Karuppasamy [27] and Hani et al. [28], who also found EOQ effective in reducing cost and stabilizing procurement under variable demand.

While the classical EOQ model focuses on economic efficiency, the present study extends its utility by using the EOQ outputs as the input layer for sustainability evaluation. This step distinguishes our approach from traditional applications that stop at cost minimization.

3.2. Sustainability Impact Analysis

In this study, sustainability aspects are explicitly positioned as evaluation indicators that assess the outcomes of EOQ-based planning, rather than as variables embedded in the EOQ formula. After determining the optimal order quantities, the results were analyzed through a set of sustainability metrics to identify the potential environmental and operational improvements achieved by the new ordering policy. From this evaluation, the EOQ–Sustainability framework demonstrated measurable performance gains. The historical surplus rate, previously averaging around 8%, declined to approximately 4% after EOQ implementation. This reduction prevented the disposal of about 20,000 packaging units annually, equivalent to nearly 4 metric tons of material waste avoided each year.

Urgent deliveries caused by stockouts were also significantly reduced. Internal logistics data showed that an average of 15 emergency shipments per month (≈ 180 annually) could be decreased by more than 70%, thus avoiding around 780 urgent deliveries. Each express refrigerated shipment emits about 5.2 kg CO_2 (DEFRA, 2023), corresponding to an estimated reduction of roughly 4,000 kg CO_2 per year. These outcomes demonstrate that improved inventory efficiency can yield indirect environmental benefits without altering the mathematical structure of the EOQ model. The findings reinforce earlier studies, such as Ahi et al. [25], who emphasized that linking inventory control to environmental metrics enhances both operational and ecological performance. Furthermore, the results echo the recommendations of Hassini et al. [26] regarding the importance of incorporating carbon-related indicators as part of post-analysis in inventory-planning models, rather than embedding them directly in cost equations.

In summary, the evaluation confirms that EOQ-based optimization can serve as a practical operational driver for sustainability performance measurement, reducing waste, curbing emissions, and improving supply reliability in vaccine-packaging management.

3.3. Safety Stock and Reorder Point

To manage lead-time variability and demand fluctuations, safety stock and reorder point (ROP) calculations were incorporated using standard deviation–based formulas. These parameters were added to complement the classical EOQ model, ensuring that the proposed ordering system remains reliable under real-world uncertainty. Table 2 presents the computed safety stock and reorder point values for each packaging material.

Table 2 – Safety stock and reorder point.

Vaccine Packaging Name	D (annual)	Safety Stock	Reorder Point
Polyurethane Box White No. 1	17.427	2.558	11.276
Polyurethane Box White No. 2	558	98	380
Vaccine & Serum Carton No. 2	1.765	598	1.486
GG Styrofoam Box (Local)	3.567	846	2.634
Cool Pack (Red, White, Blue)	427.184	66.870	280.464
Dry Ice	17.913	4.344	13.302
Freeze Alert	6.066	1.242	4.278
Vax Alert Type A.B	5.893	2.080	5.032
Vax Alert Type C	604	132	438
Logtag	1.235	242	860
Logtag WHO Type A.B	5.893	1.269	3.279
Logtag Elitech (Log ET1)	843	546	972
Plastic	7.718	1.676	5.540
Bubble Wrap	36.570	5.492	23.780
Styrofoam Sheet	26.911	4.022	17.480
Label Roll (Sticker)	72.223	9.992	46.106

The inclusion of safety stock and ROP allowed the EOQ model to better anticipate demand surges and minimize last-minute shortages, particularly during vaccination campaign peaks. This enhancement ensures inventory continuity without excessive overstocking. Moreover, validation sessions with logistics and distribution managers confirmed the practicality of these parameters, as the recommended reorder levels aligned well with actual procurement behavior and storage capacities. Stakeholders verified that these calculations would help maintain operational readiness while avoiding emergency orders that previously disrupted scheduling and increased costs.

Figure 3 presents a comparative analysis of total inventory-related expenses—including packaging procurement, holding costs, and emergency shipment costs—before and after EOQ implementation. The analysis revealed a substantial reduction in total costs, reinforcing the financial viability of the proposed strategy.

- Packaging material costs declined by approximately 33%, driven by more accurate order sizing and reduced overstocking.
- Emergency shipment costs fell by nearly 70%, as EOQ scheduling minimized last-minute logistics and premium cold-chain charges.
- Inventory holding costs decreased by about 30%, indicating improved coordination between order frequency and warehouse capacity.

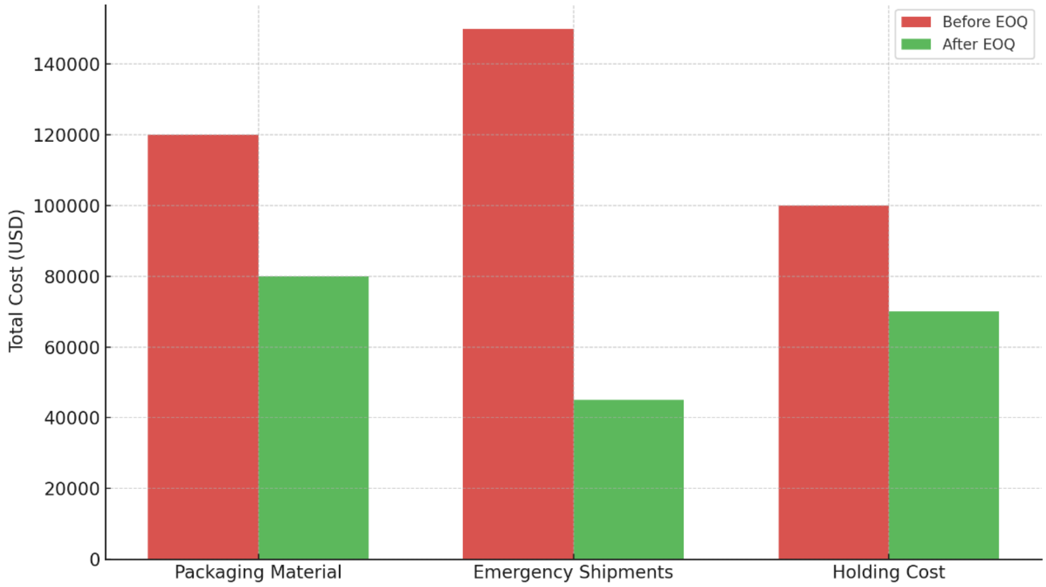

Figure 3 – Comparison of Total Cost Before and After EOQ Planning

These financial improvements are consistent with the sustainability outcomes discussed earlier, as lower emergency-shipment frequency and reduced overstocking naturally translate into less fuel usage and packaging waste. Thus, while sustainability was evaluated separately, its positive correlation with cost efficiency further validates the effectiveness of the EOQ-based framework.

In conclusion, the combined EOQ–Safety Stock–ROP model not only stabilizes inventory operations but also strengthens overall supply-chain resilience, offering both economic and environmental advantages for vaccine manufacturers.

3.4. Comparative Cost Analysis

A comparative cost analysis was conducted to evaluate the financial performance of the proposed EOQ-based system relative to the company's previous ad-hoc ordering practice. Figure 3 illustrates the changes in total cost components—ordering cost, holding cost, and emergency-shipment cost, before and after implementation.

The results show a consistent and substantial decrease in overall inventory-related expenses, confirming the economic feasibility of the EOQ-based framework. Specifically:

- Packaging material expenditure declined by approximately 33 percent, driven by more accurate order sizing and the elimination of redundant procurement.
- Emergency-shipment expenses dropped by nearly 70 percent since the EOQ schedule significantly reduced last-minute deliveries that normally incur cold-chain premium charges.
- Inventory-holding cost fell by about 30 percent, reflecting improved synchronization between purchasing frequency and available storage capacity.

Beyond cost savings, the analysis highlights improved process stability. By standardizing order intervals and quantities, EOQ planning reduced operational volatility and allowed better coordination between procurement and warehouse activities. This stability also decreased the administrative workload associated with urgent purchase orders.

The financial improvements are strongly aligned with the sustainability indicators discussed earlier. Lower emergency-shipment frequency means fewer expedited transport emissions, while reduced overstocking transfers into less unused packaging material. Although sustainability metrics were analyzed separately, their positive correlation with cost performance supports the framework’s dual value: economic efficiency and environmental responsibility.

Consequently, the comparative-cost analysis validates that EOQ supplemented with safety-stock and ROP adjustments offers a practical, data-driven approach for achieving both operational reliability and measurable sustainability outcomes in vaccine-packaging management.

3.5. Comparison with JIT and VMI Approaches

To strengthen the discussion and clarify the novelty of this research, a comparative analysis was conducted among three inventory-management strategies commonly used in supply-chain operations: Just-in-Time (JIT), Vendor-Managed Inventory (VMI), and the Economic Order Quantity (EOQ) approach adopted in this study.
The JIT system emphasizes minimal inventory levels and frequent replenishment. While JIT can be efficient in stable manufacturing environments, it is less applicable in vaccine packaging contexts where demand fluctuations, strict cold-chain requirements, and variable lead times pose significant risks of stockouts. Relying solely on JIT could jeopardize timely vaccine deliveries if supplier delays occur.

The VMI model allows suppliers to control inventory levels on behalf of the buyer. Although VMI supports collaboration and visibility, its implementation requires advanced digital integration and data-sharing infrastructure that were not yet established within the case-study organization. Moreover, VMI often prioritizes service level optimization without direct measurement of sustainability outcomes, which limits its alignment with the study’s evaluation objectives.

In contrast, the EOQ framework used here offers a pragmatic, data-driven, and easily deployable solution that balances ordering and holding costs while enabling subsequent sustainability assessment. EOQ does not rely on perfect supplier coordination but rather uses historical demand and lead-time data to create a predictable ordering schedule. By combining EOQ with safety stock and ROP adjustments, the approach achieves operational reliability comparable to VMI and stability superior to JIT, while still providing a foundation for quantifying environmental benefits.

This comparison highlights the distinctive contribution of the EOQ-based model: it bridges classical inventory optimization and modern sustainability evaluation, providing a scalable solution for healthcare logistics in developing countries where resource constraints limit the adoption of highly integrated systems.

3.6. Environmental and Operational Synergy

The results of this study reveal a strong synergy between operational efficiency and environmental performance. By stabilizing ordering patterns and minimizing last-minute shipments, the EOQ-based framework produced measurable reductions in both cost and environmental impact. Reducing emergency shipments directly lessens the use of single-use materials, such as thermal boxes, cool packs, and bubble wrap, and decreases fuel consumption from expedited cold-chain transport. The improved predictability of orders also facilitates reuse or circular-packaging practices, as packaging cycles can be planned rather than procured reactively. Avoiding just a few emergency shipments each month corresponds to tangible emission savings of several tons of CO_2 annually, which aligns with the objectives of SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). This demonstrates that operational improvements achieved through EOQ optimization inherently support sustainability goals, even when environmental factors are not mathematically embedded in the model. In summary, the framework bridges two traditionally separate dimensions—cost efficiency and ecological responsibility—showing that they can reinforce, rather than compete with, each other.

3.7. Practical Implications.

The EOQ-based sustainability-evaluation framework developed in this study offers several practical implications for practitioners in healthcare and vaccine-supply-chain management. By standardizing order quantities and intervals, the framework enhances operational reliability, helping organizations maintain adequate packaging stock levels while avoiding costly stockouts or overstocks. This stability also supports lean operations by minimizing administrative burden from emergency procurements and ensuring more predictable warehouse utilization.

Furthermore, the integration of EOQ with safety-stock and reorder-point calculations provides a cost-efficient yet resilient inventory strategy, balancing ordering and holding costs while safeguarding service levels in the cold-chain environment. From an environmental standpoint, evaluating EOQ outcomes through sustainability indicators—such as waste volume, emergency-shipment frequency, and CO_2-equivalent emissions enables organizations to quantify the indirect ecological benefits that arise from improved inventory control. In this way, operational performance and sustainability reporting become mutually reinforcing rather than separate management concerns.

In addition, the proposed framework increases decision-making transparency by promoting coordination among procurement, warehouse, and environmental management teams. This cross-functional collaboration encourages shared accountability for both financial efficiency and environmental impact. Finally, because the method relies on routinely collected operational data, it can be scaled and replicated easily across other pharmaceutical or biomedical distribution systems without the need for complex digital integration.

Overall, the findings demonstrate that classical EOQ models—when supported by real-world adjustments and evaluated through sustainability indicators—can function as practical decision-support tools for sustainable cold-chain logistics, simultaneously improving efficiency, reliability, and environmental performance.

3.6. Limitation and Future Research

Despite the promising results, several limitations of this study should be acknowledged to guide future research and application. First, the analysis relies primarily on historical demand and lead-time data, rather than on real-time monitoring or predictive forecasting. While this provides a valid baseline for evaluating the EOQ framework, it may not fully capture dynamic fluctuations in vaccine demand, supplier reliability, or external factors such as policy shifts and public health emergencies.

Second, the estimation of environmental impacts—particularly CO_2 emissions was based on standard conversion factors from DEFRA (2023), which are widely recognized but may not accurately reflect regional variations in transport modes, energy use, and cold-chain infrastructure in Indonesia. Consequently, the sustainability outcomes should be interpreted as indicative estimates rather than absolute measurements.

Third, the study's validation process was limited to internal stakeholder discussions, focusing mainly on operational and environmental dimensions. The social dimension of sustainability, such as labor conditions, supplier relationships, or community effects, was not explicitly measured, leaving room for a more comprehensive triple-bottom-line evaluation in subsequent work.

Future studies are encouraged to build upon this framework by incorporating digital and analytical enhancements. Integration with AI- or ML-based demand forecasting can enable adaptive EOQ parameters that respond dynamically to changing conditions.

Moreover, combining this model with Life Cycle Assessment (LCA) of packaging materials will provide deeper insights into long-term environmental trade-offs. The development of interactive digital dashboards could also support real-time monitoring, data visualization, and stakeholder decision-making. Finally, establishing collaborative partnerships with suppliers and logistics providers could extend the model toward a closed-loop or circular-supply-chain configuration, aligning it more closely with global sustainability frameworks.

By addressing these areas, future research can enhance both the theoretical robustness and the practical relevance of the EOQ-sustainability evaluation model, ensuring that it continues to evolve alongside emerging technologies and sustainability imperatives in healthcare logistics.

4. CONCLUSION

This study set out to address the challenge of inefficient and environmentally detrimental packaging-stock management in vaccine supply chains by applying the classical Economic Order Quantity (EOQ) model and evaluating its outcomes through sustainability indicators. The research aimed to bridge the gap between cost-efficient inventory control and environmental responsibility—a goal that has been achieved through the combination of EOQ optimization, safety-stock, and reorder-point adjustments, and post-evaluation using measurable sustainability metrics.

The findings confirm that EOQ-based planning can significantly reduce both operational inefficiencies and environmental impacts when assessed through sustainability evaluation. The case analysis demonstrated that packaging surplus could be reduced by nearly 50%, while emergency shipments and corresponding CO_2 emissions decreased by approximately 70% and 15%, respectively. These outcomes validate that classical EOQ, when applied with realistic operational adjustments, remains a powerful tool for improving both cost efficiency and ecological performance in healthcare logistics.

Importantly, the study clarifies that sustainability metrics were not embedded in the EOQ formula but rather applied as an evaluation layer to measure the environmental implications of inventory decisions. This approach contributes to the literature by extending EOQ's traditional role—from a purely cost-optimization technique to a decision-support instrument for sustainable supply-chain management (SSCM).

From a practical perspective, the proposed EOQ–Sustainability framework provides actionable guidance for vaccine manufacturers and public-health logistics planners. It enables more informed and balanced inventory decisions that minimize cost, mitigate operational risk, and align with global sustainability targets such as SDG 12 and SDG 13. The framework can be readily implemented using existing data systems, making it suitable for organizations in developing countries seeking to strengthen their cold-chain resilience without major infrastructure investment.

Future research should focus on enhancing this model's adaptive capability through integration with AI-driven forecasting, Life Cycle Assessment (LCA), and digital dashboards for real-time sustainability tracking. Extending collaboration with suppliers and stakeholders could also help develop closed-loop inventory systems, reinforcing circular-economy principles in vaccine logistics.

In summary, this research demonstrates that operational excellence and environmental sustainability are not competing objectives but mutually reinforcing elements of modern supply-chain management. By positioning EOQ as both a cost and sustainability evaluation tool, this study offers a practical contribution toward achieving more adaptive, efficient, and sustainable vaccine distribution systems.

Acknowledgement

The authors would like to express their sincere appreciation to Telkom University for the academic and logistical support that made this study possible. Special thanks are also extended to the Distribution Department of the participating vaccine manufacturer in Bandung, Indonesia, for granting access to operational data and for their active collaboration during the fieldwork and validation phases.

The authors are also grateful to the colleagues and reviewers whose constructive feedback significantly improved the quality and clarity of this paper. Their insights helped refine the interpretation of sustainability as an evaluation dimension within classical inventory theory.

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