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Cold Chain Optimization in the Food Industry: Integration of IoT-Based Monitoring and Modified Atmosphere Packaging Using High-Barrier Mono-Material

Nurhayati*, Felycia Angellia, Jolie Verlita, Malvin Widyanto Tjoa, Felicia Novia Alverina, Made Grazielle Hillary Yadi

Universitas Prasetiya Mulya

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*Correspondence: Nurhayati
Email: nurhayati@prasetiyamulya.ac.id

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Abstract: *This study evaluates the integration of Internet of Things (IoT)-based temperature monitoring and high-barrier mono-material Modified Atmosphere Packaging (MAP) as a strategy to reduce food loss in cold chain systems. The research assesses the technical, environmental, and economic implications of implementing real-time temperature control alongside recyclable packaging materials. The results indicate that IoT-based monitoring reduces spoilage by enabling rapid detection of temperature deviations and corrective actions during storage and transportation. In parallel, high-barrier mono-material MAP maintains internal gas composition, extending shelf life and stabilizing product quality throughout distribution. Life cycle and techno-economic considerations suggest that although initial investment and material costs may increase, reductions in food loss and improved sell-through can offset expenses, particularly for high-value perishable products. Overall, the integration of digital monitoring and barrier packaging provides a preventive and preservative approach that enhances cold chain performance, reduces waste, and supports environmental sustainability.*

Keywords: *Cold Chain Optimization, Internet of Things, Modified Atmosphere Packaging, Mono-Material Packaging, Food Loss Reduction*

Introduction

Cold chain systems play a critical role in maintaining the quality, safety, and shelf life of perishable food products throughout storage and distribution (Masyitho et al., 2023). However, the implementation of cold chain systems in Indonesia still faces several challenges related to operational aspects, technology, human resources, unstable electricity supply, high investment costs, infrastructure limitations, and other factors. The main issue identified is the uneven distribution of cold chain infrastructure. This limitation can be observed in the availability of cold storage facilities, refrigerated vehicles, and distribution centers, which remain concentrated in major cities, particularly on Java Island, while other regions outside Java are relatively underdeveloped (Vikaliana, 2019). A study conducted by Evitha (2019) revealed that cold chain infrastructure in Indonesia is still inadequate and unevenly distributed, resulting in an insufficiently integrated distribution network. These constraints contribute to ineffective temperature control, increasing the risk of product deterioration and food loss across the supply chain.

Furthermore, when infrastructure is uneven and transportation distances are long, cold chain logistics become more complex, an issue particularly relevant for Indonesia as an archipelagic country. National cold storage infrastructure remains limited and largely concentrated in urban areas and major islands such as Java, whereas many outer regions, including eastern Indonesia, have significantly lower capacity. Inter island distribution often relies on sea and air transport, which requires higher costs and poses greater risks of temperature fluctuations during transit. The lagging logistics conditions and insufficient coordination among supply chain nodes further hinder efforts to maintain product quality during distribution and increase the risk of food loss due to greater levels of food spoilage throughout the distribution process (Han et al., 2026).

Most existing studies focus on advanced monitoring technologies such as Radio Frequency Identification (RFID) which require high investment and complex implementation (Evitha, 2019). However, limited research explores cost-effective and practical real-time monitoring solutions that can be applied in resource constrained cold chain systems. RFID systems require additional investment ranging from tens to hundreds of millions of rupiah, depending on the number of sensors, readers, and software integration systems employed (Zuo et al., 2022). Furthermore, the energy required to maintain consistently low temperatures incurs very high costs, with energy consumption accounting for approximately 60% of total operational expenses (Wang & Du, 2025). This situation becomes even more complex when faced with unstable electricity supply in certain regions, which may lead to temperature fluctuations during storage and distribution processes (Evitha, 2019). Such temperature variations pose a risk of reducing food product quality and further weakening the overall performance and reliability of the cold chain system.

Another issue is the limitation of human resources (HR) and technical operational capacity. There are still relatively few logistics operators and food business owners who have adequately trained personnel. Therefore, limited knowledge of monitoring technologies and insufficient human resource competence constitute major factors contributing to failures in temperature control throughout the cold chain, particularly for temperature-sensitive products (Wu & Hsiao, 2020; Mustafa et al., 2024).

The urgency of this issue is reflected in the high level of food loss and waste in Indonesia, which reaches tens of millions of tons annually (Baity & Afinnas., 2025). Ineffective temperature control during storage and distribution remains one of the main contributing factors to this problem. Therefore, there is a need for preventive and adaptive solutions that can improve cold chain performance under existing limitations.

Therefore, this study aims to analyze the optimization of the cold chain system in supporting the sustainability of the food industry through the implementation of the Internet of Things (IoT) as a real-time temperature monitoring system and the use of more sustainable High-Barrier Mono-Material packaging. This study focuses on efforts to reduce food loss and waste caused by cold chain inefficiencies, while simultaneously improving product quality and minimizing environmental impacts within the food supply chain.

Methodology

Research Design

This study employed a qualitative approach using a Systematic Literature Review (SLR) design to examine the uneven implementation of cold chain systems and the distribution challenges of temperature-sensitive food products, as well as to explore potential solutions to improve the effectiveness of cold chain systems. The review also analyzed the relationship between cold chain performance and the increase in food loss and waste, along with its impact on packaging waste within the food supply chain. This study supports one of the ten principles of the Sustainability Food Industry, namely Principle 9: How to Manage Food Waste. The SLR design was selected because it enables the researcher to systematically collect, compare, and filter various scientific findings in order to develop a comprehensive understanding of the relationship between suboptimal cold chain systems, the need for more affordable temperature monitoring solutions, and sustainability implications within the food system.

Research Procedure

The research procedure was conducted in several sequential stages following the PRISMA framework. The first stage involved a literature search using reputable scientific databases such as ScienceDirect, MDPI, Google Scholar, MDPI, Scopus, and PubMed. The keywords used in the search process included “cold chain system,” “cold chain infrastructure,” “temperature-controlled supply chain,” “IoT in cold chain,” “food loss and waste,” as well as other relevant keyword combinations aligned with the research context. The sampling technique employed was purposive sampling, in which articles were selected based on their relevance to the research focus according to predetermined criteria. The included literature consisted of peer-reviewed journal articles published within the last ten years (2016–2026), available in full text, and specifically addressing cold chain systems, temperature control, the application of IoT in food logistics, or their impact on food loss and food waste. Articles that were irrelevant, lacked clear scientific sources, or did not directly address the topic were excluded from the sample.

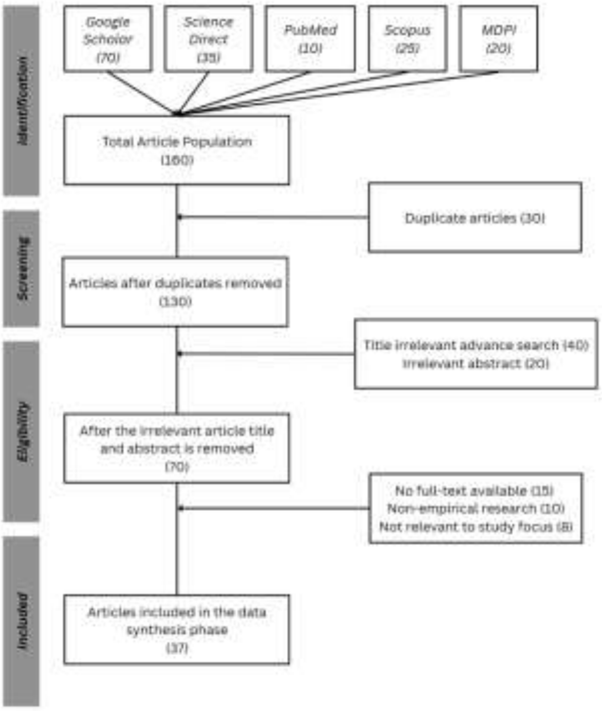

Figure 1. PRISMA Framework

Based on the PRISMA framework the study selection process was conducted systematically through identification, screening, eligibility, and inclusion stages. A total of 160 articles were initially identified during the identification stage. After removing duplicates, only 130 articles remained for screening. The second stage involved a screening process by reviewing the titles and abstracts to ensure topic suitability, resulting in 70 articles considered relevant. The third stage consisted of a full-text review to gain a comprehensive understanding of the content and to assess the quality and relevance of each article from which 37 articles met all inclusion criteria and were included in the review for in-depth analysis.

The subsequent stage involved analyzing and synthesizing the findings from the selected literature to identify patterns, similarities, differences, and research gaps. The synthesized results were extracted and then organized using a qualitative thematic synthesis approach, The synthesis process involved three main steps starting from data extraction and coding, thematic grouping, and interpretative synthesis. Data extraction and coding is the process that identifies key findings and categorizes them into thematic variables. Then, grouping similar findings to identify patterns, similarities, and differences. The last step is by integrating the findings into a coherent and logical narrative to construct an argument regarding the urgency of implementing simple IoT solutions to improve cold chain performance.

Instrument

The primary instrument in this study was the researcher, who played a central role in the processes of literature searching, selection, evaluation, interpretation, and synthesis.

To ensure consistency and objectivity in the analysis, the researcher applied a structured literature review guideline that included criteria such as topic relevance, source quality (journal indexing and reputation), contribution to cold chain and sustainability issues, and relevance to the context of food loss and food waste. By employing a structured analytical framework, this study is expected to produce a systematic, valid, and comprehensive discussion aligned with the objectives of the review.

Result and Discussion

Justification of Low-Cost Temperature Monitoring

The selection of a low-cost technology-based temperature monitoring solution is based on both cost issues and the real challenges faced by people in the cold chain in areas with limited resources and poor infrastructure. Although technologies such as RFID and integrated traceability systems provide better visibility across the supply chain, many studies show that cost and complexity are the main reasons why companies don't adopt them. A study by Masekwana and Jokonya in 2025 looking at how RFID is used in food systems finds that the main reason people don't adopt it is because of the high cost to start, plus the need for advanced technology to set it up. This finding is supported by a wider study looking at IoT in food supply chains, which shows that while IoT greatly helps with tracking food and keeping it at the right temperature, high costs, worries about keeping data safe, and rules that are hard to follow still stop people from using this technology. This is especially true in poorer areas, where there's a big difference in how advanced the technology is between large companies and smaller ones (Ahmad et al., 2024).

Besides cost, the need for real-time temperature data quickly becomes a strong reason to choose a low-cost solution instead of more complicated options. Masudin et al. (2021) show that having quick and easy access to information is very important in cold food supply chains. This is because the food items are easily spoiled and don't last very long. The paper also shows that traceability systems have a clear and important positive impact on how well the cold chain works, providing solid proof that improvements in monitoring can be effective even when using basic technology. This viewpoint is important because it changes the way we look at things from focusing on how advanced the technology is to looking at how well it works in practice. This difference is especially important for people or groups that don't have the money or the technical skills to use high-level, big company solutions.

However, importantly, when comparing different ways of monitoring, there are various trade-offs that the current research doesn't always cover in a consistent way. Some studies on LoRa-based IoT systems say that each sensor node costs between 30 and 80 euros, and gateways cost between 200 and 1,000 euros. This setup is expected to give a good return on investment after one or two farming seasons, mainly because it helps reduce waste and saves on labor costs (Protopappas et al., 2025). In comparison, prototype modular systems show that component costs can go as low as about USD 180 each, and becoming more cost-effective happens a lot when producing in larger amounts (Shah, 2019). These numbers show a big difference compared to RFID systems, which have much higher costs for each unit and need more complicated software to work with. This comparison between studies shows that the low-cost limit isn't the same for all products or sizes. It depends on the type of product and how much is being handled. So, the reasons for keeping costs low need to be looked at carefully, based on each situation, not just applied generally to the whole cold chain industry.

Another important point for critical analysis is the real-time alert feature, which is now seen as the main advantage of using IoT for monitoring. Studies show that combining IoT and AI in cold chain systems helps detect quality issues early by using real-time data from sensors. This reduces food spoilage and waste during storage and transportation (Müller et al., 2026). Gillespie et al. (2023) also point out that threshold-based notifications are meant to prevent issues before they happen, not just to check things after the fact. When you look at all these studies together, they show that the main benefit of using IoT instead of manual recording isn't about having more data, but about getting the signal for action faster. This insight is a new contribution of this paper: instead of suggesting that IoT should completely replace existing traceability systems, the study views it as a focused addition that improves operational resilience, especially in the area between storage and distribution where monitoring is lacking. Neither RFID nor manual logging fully addresses this gap, especially when resources are limited.

Proposed System Design

An IoT based architecture gives a viable and cost-effective approach to continuous temperature recording within cold storage facilities. Compared to periodic manual data collection, which is prone to human error, IoT sensor transmit data wirelessly to cloud platforms at configurable intervals, enabling remote and real-time monitoring without complex technical infrastructure. This approach is consistent with findings across studies, which shows that environmental monitoring significantly reduces the probability of undetected temperature monitoring, which is the primary cause of cold chain food loss (Cil et al., 2022; Gilliespie et al., 2023).

From a system design point of view, sensor placement at critical control points within cold storage, such as near doors, thermal zone, and product stacking area is essential to capture the whole variability of temperature distribution. The data collected by sensor nodes is transmitted to cloud repositories, where it can be analyzed for trend identification and visualized through dashboard to support decision making. Gillespie et al. (2023) state that IoT based monitoring has demonstrated significant capability in detecting deviations from target temperature ranges, achieve energy saving, and enable faster preventive intervention compared to manual recording. The benefits are not only operational, but also economic, and faster detection which can reduce product degradation of product.

Compared to RFID, which requires proximity based readers, fixed infrastructure, and higher per-unit cost, IoT wireless sensor networks gives more scalable and less infrastructure dependent alternative for temperature monitoring, although they do not provide item level traceability. The trade-off of the proposed design is optimized for environmental parameter tracking rather than product value, which aligns with the objective of this article.

Modified Atmosphere Packaging using High-Barrier Mono-Material

Modified Atmosphere Packaging or MAP is a widely used method to extend the shelf life of fresh foods by adjusting the gas composition inside the package, which helps slow down microbial growth and oxidation. Its effectiveness has been reported across many types of products, with the level of shelf life improvement depending on factors such as the type of food, gas composition, storage temperature, and packaging material. MAP can extend the shelf life of fruits and vegetables by around 50% to 200% compared to normal air conditions. For example, strawberries stored under MAP with 5% oxygen and 15% carbon dioxide can last up to 14 days without quality loss, compared to only 4–5 days at room conditions. For meat products, the use of high carbon dioxide levels has been shown to increase shelf life by about 40–60% compared to conventional packaging (Habiba et al., 2025). The main mechanism behind this improvement is the suppression of microbial growth across product categories (Rasheed et al., 2025), while MAP can double the shelf life of fresh pasta from 20–40 days and increase it by 3–6 times for fresh cheese filled pasta when combined with high-barrier mono-material packaging (Bauer et al., 2022).

A closer look at these studies shows an important limitation. Most of the reported shelf life improvements are obtained under controlled laboratory conditions and may not be fully achieved in real cold chain systems. In real situations, temperature changes, possible packaging damage, and differences in handling can affect the results. This gap between laboratory results and real world performance is often not discussed in enough detail in MAP studies. It also shows the importance of combining MAP with other solutions, such as real-time temperature monitoring, instead of relying only on packaging to reduce food loss. The performance of MAP depends strongly on the barrier properties of the packaging material. If oxygen can easily pass through the packaging, the modified atmosphere inside cannot be maintained, which reduces its effectiveness. Traditional multilayer packaging, made from materials such as PET, PA, and EVOH with adhesive layers, provides very good barrier properties but creates challenges in recycling because the materials are difficult to separate using standard methods (Siracusa, 2012; Guerritore et al., 2021). As an alternative, high-barrier mono-material packaging based on polyolefins such as polyethylene and polypropylene, sometimes combined with EVOH layers or coatings, has been developed to improve recyclability while maintaining performance. These mono material structures are able to maintain the gas composition required for MAP and at the same time offer better recycling potential compared to multilayer films (Guerritore et al., 2021).

When comparing these options, the differences in performance need to be considered carefully. Multilayer films are still the best option for achieving very high-barrier performance, especially for sensitive products like raw meat and fresh seafood, where even a small amount of oxygen can speed up spoilage. Mono material polyethylene and polypropylene films with added barrier layers can reach similar performance in some cases, but may not fully match multilayer systems for products that are highly sensitive to oxygen (Mengozzi et al., 2024). Therefore, the choice of mono material MAP should depend on the type of product. It is more suitable for products with moderate barrier needs, where the benefit of better recyclability can be more important than a small difference in performance.

For products that require very high protection, multilayer packaging may still be the better choice, especially if recycling systems are limited. Clearly stating this trade off gives a more balanced and critical view than what is usually found in packaging studies.

Impact on Food Loss

The combined use of real-time IoT temperature monitoring and MAP with high-barrier mono-material packaging forms a two layer approach with complementary roles in reducing food loss. IoT monitoring focuses on the process aspect by identifying and correcting temperature deviations before irreversible product damage occurs, while MAP focuses on the product itself by extending its natural shelf life and providing a wider buffer against unavoidable variations in cold chain conditions (Gillespie et al., 2023). This difference in how each intervention works is important from an analytical perspective, yet it is often overlooked in existing studies, which tend to treat food loss solutions as interchangeable rather than recognizing their distinct mechanisms. Evidence on the impact of IoT in reducing food loss is most convincing when compared with conditions before implementation. A long range based cold chain monitoring study in Spain on citrus exports showed that spoilage rates dropped from about 8.3% to 2.5% after IoT adoption, representing a reduction of nearly 70% (Protopappas et al., 2025). A similar case in Italy reported a 40% decrease in fungal infections and a 5% increase in marketable yield due to improved control of temperature and humidity in greenhouse systems (Protopappas et al., 2025). In addition, measurable reductions in spoilage have been linked to faster detection of temperature disruptions in fruit supply chains (Mercier et al., 2017). These findings suggest that real-time monitoring can significantly reduce food loss in practice, while the scale of impact varies depending on the type of product, supply chain conditions, and the initial level of cold chain inefficiencies.

For MAP, the extension of shelf life observed in laboratory and semi commercial settings directly lowers the risk of spoilage during storage and distribution, which is the key connection to food loss reduction. MAP has been estimated to help address up to 1.3 billion tonnes of global food waste each year by slowing spoilage (Habiba et al., 2025). However, this estimate should be understood as a theoretical upper limit rather than an outcome consistently achieved in real conditions. A more cautious interpretation, in line with life cycle assessment approaches, suggests that the overall benefit depends on whether the reduction in spoilage is greater than the additional environmental and resource impacts associated with the packaging (Sasaki et al., 2024). This condition is an important consideration and raises the standard of evidence needed when positioning MAP as a solution to food loss compared to more straightforward preservation methods. Across both approaches, comparisons between studies point to a consistent conclusion that food loss reduction is most effective when monitoring and packaging are used together rather than separately. IoT monitoring alone cannot extend the biological shelf life of a product once there has been a temporary failure in the cold chain, while MAP alone cannot fully address situations where temperature deviations are severe or prolonged and disrupt the intended gas conditions inside the package. Combining these two approaches creates a more resilient system than using either one on its own.

Economic Impact

The economic justification for IoT based temperature monitoring in cold chain is product dependent and scale dependent, based on study comparisons. Lamberty and Kreyenschmidt (2025) state from stakeholder interviews that profitability of IoT adoption varies by commodity, transport mode, and shipment frequency. Highly perishable and high value products like strawberries and vine tomatoes gives higher economic return from IoT than lower sensitivity commodities. This finding is consistent with the broader observation that the cost of goods lost to spoilage usually exceeds sensor deployment costs for temperature sensitive and high value produce (Mokosmart, 2024).

Empirical data from the SmartColdChain EU Project indicate that IoT automation can yield 20-30% operational cost savings and reduce manual temperature checks by more than 60%, lowering labor costs (Protopappas et al., 2025). IoT systems have shown component costs as low as around USD 180 per unit, with economic viability improving significantly at production scale (Tandfonline, 2025).

For MAP with high-barrier mono-material, the economic is based on material cost of high-barrier films compared to conventional packaging by improvements of sell-through rate, reduction in product returns, and lower waste management costs. Bauer et al. (2022) shows this positive economic balance for fresh pasta and cheese-filled pasta, where shelf life is longer compare to conventional packaging generates a nice improvement in distribution windows and commercial viability. Importantly, mono-material structures gives an additional long-term economic benefit through improved recyclability, which reduce waste sorting and aligns with the EU Packaging and Packaging Waste Regulation, that requires all plastic to be recyclable by 2030 (Greenglobalink, 2025).

A critical comparison of the two interventions from an economic standpoint reveals an asymmetry in cost structure and risk profile. IoT monitoring carries higher upfront capital costs with variable returns dependent on product type and supply chain configuration, while MAP with mono-material carries a more predictable incremental material cost with more uniform returns across product categories. This asymmetry suggests that the two interventions may appeal to different segments of cold chain actors: IoT adoption is most defensible for mid to large scale operators handling high-value, temperature-sensitive products, while MAP adoption may be more broadly accessible across operator scales. This differential accessibility analysis is an original contribution of this paper, as the existing literature does not systematically compare the economic feasibility profiles of these two interventions side by side.

Sustainable Implication

The sustainability implications of integrating real-time IoT monitoring with MAP using high-barrier mono-material packaging cover environmental, economic, and social aspects, and require a more careful and differentiated analysis than the broad claims often found in existing literature. From an environmental perspective, the most direct and widely recognized benefit of these interventions is in reducing food loss and waste. A systematic review shows that real-time monitoring technologies enable continuous tracking and early detection of quality deviations across storage and distribution stages, contributing to measurable reductions in food loss and waste (Da Costa et al., 2023). Food loss and waste are associated with inefficient use of land, water, and energy, as well as unnecessary greenhouse gas emissions from food that is produced but not consumed. Therefore, reducing these losses through monitoring also generates upstream environmental benefits beyond the cold chain itself.

For MAP, the contribution to sustainability works through a different pathway. By extending product shelf life, MAP lowers the frequency of spoilage related disposal and the associated emissions within the food system. This contribution is often discussed in relation to the global scale of food waste, which is estimated at around 1.3 billion tonnes annually, where MAP is considered to play a meaningful role in reducing these losses (Habiba et al., 2025). Recent developments also highlight the use of fiber based MAP trays made from renewable materials such as sugarcane bagasse, which can reduce plastic content by about 85% while still maintaining the necessary oxygen and moisture barrier properties for preserving meat and seafood. These material innovations suggest a growing alignment between MAP performance and circular economy principles, although the trend has not yet been extensively explored in the literature.

When comparing sustainability outcomes across monitoring and packaging approaches, it becomes clear that the environmental benefits of both depend on broader system conditions that are often not fully considered in individual studies. For IoT, the overall environmental gain depends on whether the reduction in food loss is greater than the energy required for sensing, data transmission, and cloud based processing (Da Costa et al., 2024; Pirson & Bol, 2021). For MAP with mono-material packaging, the net benefit depends on whether the extension of shelf life outweighs the additional inputs related to materials and gas usage. Life cycle assessment studies show that this balance is influenced by the type of material, the product category, and the availability of local recycling systems (Sasaki et al., 2024). Recognizing these conditions clearly and presenting sustainability as context dependent rather than absolute is an important analytical contribution compared to studies that make unqualified claims.

From a social sustainability perspective, the issue of inclusive access to these technologies requires more attention than it usually receives in cold chain research. High investment costs and limited access to digital infrastructure remain barriers to the adoption of food loss reduction technologies, particularly among small scale producers in lower income settings (Benyam et al., 2021). The focus on low cost IoT solutions in this study addresses part of this challenge, but affordability is not sufficient, as effective adoption also depends on training, operational support, infrastructure readiness, and access to inclusive financing (Ahmad et al., 2024). In a similar way, while mono-material MAP improves recyclability, it may create challenges in regions where recycling infrastructure is not well developed. In such cases, the expected environmental benefits may not be fully realized and could even lead to increased plastic waste at the end of the product life cycle. These social and infrastructure related conditions are still not well explored in current MAP research and represent an important area for future study.

Sustainable Limitation

Using both IoT monitoring and MAP along with high-barrier mono-materials can help prevent food waste in a useful way. However, it's important to carefully examine the environmental and social effects of these methods to understand their real impacts. These limitations don't reduce the value of the proposed approach, but they set the conditions under which the sustainability claims in this paper are valid, something that's often missing in single-intervention studies that report benefits on their own.

For IoT-based monitoring, the biggest environmental problem is related to energy use and the amount of electronic waste created. As the system grows larger, the need for constant monitoring, sending data wirelessly, and using cloud computing keeps electricity use high, so it's important to compare this energy use with the benefits of reducing food waste (Da Costa et al., 2024). Research on the environmental impact of commonly used electronic devices throughout their life cycle shows that when a lot of IoT devices are used, it's important to carefully check the effects to avoid making the environment worse because of making the devices, replacing batteries, and throwing them away (Pirson & Bol, 2021). If there are no good ways to manage things, using more IoT devices could lead to a lot of electronic waste (Razip et al., 2022). This issue is especially serious in developing countries, where the systems for handling e-waste are not well established. This means that even though IoT monitoring systems might work well during their use, they can lead to big environmental problems when they are no longer needed. These environmental impacts happen later, but most assessments that look at sustainability don't take this time gap into account.

A comparison of different studies on the sustainability of IoT shows that the balance between saving energy and reducing food waste depends a lot on the specific situation. Studies on smart shelf life systems using IoT in China's cold chain logistics show that the amount of greenhouse gases saved by reducing food waste through these systems is much larger than the emissions from the sensors themselves. This is especially true as China's power grid moves towards cleaner energy sources (Wu et al., 2025). But this good balance might not work in situations where there's more carbon in the power system, longer paths for getting devices, or less waste in food already. This means that how sustainable an IoT system is doesn't come from the technology itself, but depends on the energy system and supply chain it's part of—so this important point needs to be clearly mentioned when comparing the sustainability of different systems.

For materials with high-barrier mono-materials used in MAP, the main issue for sustainability is the conflict between how well they block things out and how easy they are to recycle. Even though using single-material PE and PP structures is a big improvement compared to older multilayer composites, adding more barrier layers like EVOH coatings and special surface treatments makes the materials more complicated. This complexity can lower the quality of recycled materials in mechanical recycling processes (Guerritore et al., 2021). Research on high-barrier flexible films shows that making these materials recyclable from the start is still a big challenge. The same features that make them good at blocking gases often make it hard to recycle them using current systems (Mengozzi et al., 2024). This issue hasn't been fully settled in scientific research papers yet, and studies on the entire life cycle show that how well MAP performs environmentally depends a lot on whether the packaging gets properly recycled at the end of its use (Sasaki et al., 2024; Habiba et al., 2025).

Another problem is the gas flushing step in MAP, which uses up CO_2 and N_2, and the amount used depends on the type of product and the size of the package. These process gases are usually made as byproducts in industries, and releasing them directly doesn't cause much environmental harm. However, the energy needed to compress, store, and control the gas adds to the total environmental impact of MAP systems. Studies on the life cycle of fresh pasta packaging show that the overall environmental impact of modified atmosphere packaging (MAP) can change depending on the type of material used, how it's stored, and the conditions set for the assessment. This means that even when using high-performance single-material options, the environmental effect can vary a lot. (Bauer et al., 2022; Sasaki et al., 2024) This sensitivity shows why it's important to use life cycle assessments that are specific to each product and situation, instead of making broad sustainability statements. This is a key area for future research that builds on the framework presented in this paper.

In the end, both methods have a shared problem when it comes to social sustainability: the chance that the benefits might not be spread fairly. If the benefits from using IoT in the food system mostly go to big, well-funded companies that handle cold storage, and if using single-material modified atmosphere packaging depends on having recycling facilities that are mostly found in wealthy city areas, then both of these technologies might actually make inequality worse instead of helping to make food systems more sustainable (Benyam et al., 2021; Ahmad et al., 2024). To address this fairness issue, we need more than just new technology. We also need rules and policies that help everyone get access—like programs that offer cheaper devices, creating free or low-cost software platforms, and building recycling systems in areas that are not getting enough support. These governance aspects are not covered in the technical analysis here, but they are an important part that goes along with the cold chain optimization framework proposed.

Conclusion

This study demonstrates that integrating real-time IoT-based temperature monitoring with high-barrier mono-material Modified Atmosphere Packaging constitutes a complementary dual-layer strategy for reducing food loss in cold chain systems. IoT monitoring addresses the process dimension by enabling early detection and correction of temperature deviations, while MAP addresses the product dimension by extending intrinsic shelf life through controlled internal atmospheres. Together, these interventions create a more resilient system than either approach independently.

However, several limitations must be acknowledged. The sustainability benefits of both technologies are context-dependent: IoT energy consumption and electronic waste generation can offset food loss reduction gains in carbon-intensive or e-waste-limited settings, while MAP's environmental performance is contingent on effective end-of-life recycling infrastructure that remains unevenly distributed. Additionally, high upfront costs and the digital divide constrain equitable access, particularly for small-scale operators in developing regions.

Future implementation should therefore be guided by three practical recommendations. First, IoT adoption should be prioritized for high-value, temperature-sensitive commodities where spoilage costs demonstrably exceed monitoring investment. Second, MAP material selection should be product-specific, with mono-material structures favored where barrier requirements are moderate and local recycling systems are functional. Third, policy frameworks must complement technical solutions through inclusive financing mechanisms, capacity building programs, and investment in recycling infrastructure in underserved regions. Addressing these dimensions collectively will determine whether cold chain optimization delivers both food security and sustainability outcomes at scale.

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