Comparative Evaluation of Ammonia (R-717) and Isobutane (R-600a) for Cold Storage Systems: Energy Efficiency, Environmental Impact, and Safety Considerations

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Abstract

Cold storage refrigeration systems contribute to environmental concerns because they widely use refrigerants with high global warming potential (GWP) and ozone depletion potential (ODP). The transition toward environmentally sustainable refrigeration technologies requires alternative refrigerants that provide high energy efficiency while satisfying environmental and safety requirements. This study investigates ammonia (R-717) and isobutane (R-600a) as alternative refrigerants for cold storage applications, focusing on energy performance, environmental impact, and safety aspects. A vapor compression cycle model was simulated under typical operating conditions (evaporator at –25 °C, condenser at 40 °C, and cooling load of 25 kW). The results indicate that R-717 achieved the highest coefficient of performance (COP = 2.02) with minimal energy losses but requires strict safety controls because of its toxicity. R-600a exhibited a slightly lower COP (1.82) but an almost negligible global warming potential and ozone depletion potential. Both refrigerants offer efficient, sustainable alternatives to conventional refrigerants, supporting the transition to low-emission cold chain systems aligned with the Montreal Protocol and Kigali Amendment goals.

***Keywords**:* ammonia (R717), cold storage refrigeration, environmental impact, isobutane (R-600a), thermodynamic performance

1. Introduction

Food preservation remains a pressing issue, with an estimated 1.3 billion tons of food wasted worldwide each year, as reported by the Food and Agriculture Organization (FAO) (Leungtongkum *et al.*, 2022). This challenge is especially acute in cold chain logistics, which plays a critical role in the food supply chain from production to consumption. Cold chain logistics involves complex processes, including transportation and warehouse storage, and relies heavily on refrigeration systems to maintain the temperatures needed to preserve perishable goods (Zhao *et al.*, 2018).

In transportation, the cold chain aims to ensure that food products, often sensitive to temperature fluctuations, reach their destination without compromising quality or safety (Tao *et al.*, 2023). This involves a network of refrigerated vehicles, such as trucks and containers, equipped to maintain specific temperature ranges throughout the journey. The cold chain is an intricate system that requires balancing cost efficiency, timeliness, product quality, environmental considerations, and the unique technical challenges of managing perishable cargo (Fan *et al.*, 2021).

While refrigeration systems play a pivotal role in preserving food, they introduce a paradoxical challenge. The performance and long-term sustainability of cold storage refrigeration systems are often constrained by the environmental impacts and operational limitations of conventional refrigerants. Cold storage systems require refrigerants that simultaneously optimize thermal performance, minimize environmental damage, and maintain safety, a balance not fully achieved by currently dominant refrigerants. The very systems designed to prevent food spoilage contribute to environmental issues, primarily because of the refrigerants they use (Dong & Miller, 2021). These refrigerants, commonly hydrofluorocarbons (HFCs) and chlorofluorocarbons (CFCs), are significant contributors to ozone depletion and global warming (di Filippo *et al.*, 2022; Aisyah & Ariyadi, 2024). As a result, there is a pressing need to address the environmental impact of these refrigerants and develop alternative solutions that balance efficient cooling with environmental sustainability.

Efforts to mitigate the environmental impact of cold chain logistics focus on evaluating potential refrigerants for cold storage systems (Benhadid-Dib & Benzaoui, 2012). The goal is to develop a cooling system that effectively preserves food while reducing its environmental impact. This requires an in-depth evaluation of the fundamental properties and performance metrics of alternative refrigerants. A crucial criterion in this assessment is the thermodynamic properties of potential refrigerants, which are instrumental in determining their heat absorption and release efficiency. An ideal refrigerant should exhibit a high COP, reflecting superior heat transfer capabilities. Additionally, environmental impacts extend beyond energy efficiency, including the global warming potential (GWP) and ozone depletion potential

(ODP) of refrigerants. GWP assesses the relative impact of greenhouse gas over a designated period in comparison to carbon dioxide, whereas ODP measures a substance's capacity to erode the ozone layer. Growing concerns about global warming and ozone layer depletion led to the establishment of the Montreal Protocol in 1987, which regulates refrigerant use to mitigate these environmental threats (Astrain *et al.*, 2019).

The transition to alternative refrigerants introduces a complex array of challenges beyond their environmental advantages. Existing infrastructure, primarily designed for conventional refrigerants, often requires significant modifications or complete replacement to accommodate new, environmentally friendly alternatives. This transition entails not only retrofitting current refrigeration systems but also comprehensively redesigning components and equipment. Such redesigns are essential to adapt to and optimize for the distinct characteristics of alternative refrigerants, ensuring efficient performance and compatibility with the latest environmental standards (Kivevele, 2022). Furthermore, the safety landscape undergoes a critical reassessment during this transition. Safety standards and regulations must be meticulously updated to account for the distinctive properties of alternative refrigerants, addressing concerns related to toxicity, flammability, and compatibility with the existing infrastructure. Proper handling, storage, and operation of these new refrigerants must be prioritized, requiring comprehensive training programs and guidelines to protect personnel and the surrounding environment. The successful adoption of alternative refrigerants hinges on a holistic approach that considers technical, safety, and regulatory aspects to support a smooth, secure transition away from traditional options.

Several alternative refrigerants are being explored as potential solutions to the environmental challenges posed by traditional refrigerants. Natural refrigerants, including ammonia, carbon dioxide, hydrocarbons, and even water are gaining attention for their lower environmental impact and energy efficiency (Ariyadi & Coronas, 2016; Ariyadi *et al.*, 2019a; Ariyadi *et al.*, 2019b; Hadi *et al.*, 2023; Tanbar *et al.*, 2024; Ariyadi *et al.*, 2025; Aisyah *et al.*, 2025; Yıldırım *et al.*, 2025). Ammonia, in particular, has been used in industrial refrigeration for decades because of its excellent thermodynamic properties and minimal environmental impact. Hydrocarbons, such as propane and isobutane, are also being explored as environmentally friendly alternatives. These refrigerants have low GWP and ODP values, making them attractive options for reducing the ecological impact in cold chain logistics

(Dreepaul, 2017), commercial, and domestic refrigeration, particularly in household refrigerators and freezers (Arumuganainar *et al.*, 2025; Borokinni *et al.*, 2026; Gyimah *et al.*, 2026). However, safety considerations, including flammability and explosion risks, must be addressed in the design and operation of systems using hydrocarbon refrigerants (Colbourne & Suen, 2004; Li *et al.*, 2025; Olufunke Bolaji *et al.*, 2025; Prakopavičius & Vaitkus, 2026). Therefore, assessing their performance against these refrigerants underscores the need for a balanced approach considering both efficiency and safety (Hao *et al.*, 2025; Karakaya *et al.*, 2025).

This research undertakes a detailed assessment of R-717 and R-600a as viable alternatives to traditional refrigerants, emphasizing their efficiency, reduced environmental footprint, and adaptability for cold chain logistics. The evaluation rigorously analyzes performance, environmental implications, safety considerations, and specific operational demands. This aims to determine the feasibility of integrating these refrigerants into existing systems while supporting broader sustainability and regulatory compliance in refrigeration practices. The primary objective is to identify R-717 and R-600a as the most appropriate alternative refrigerants to maintain optimal cold storage conditions within the critical temperature range of -18 °C to -20 °C, with particular emphasis on reducing environmental impact and mitigating potential system hazards. This research provides a comprehensive analysis to deliver actionable insights that could inform decision-making in the design and operation of cold storage facilities. The evaluation seeks to support the transition to more sustainable and robust cold chain systems, thereby enhancing operational efficiency and promoting environmental responsibility within the logistics and transportation sectors.

2. Methodology

2.1 System Description

Figure 1 shows the thermodynamic process in a vapor compression refrigeration system operating under steady-state conditions on a T-s diagram. The cycle consists of four main stages: isentropic compression (1-2), isobaric heat rejection (2-3), isenthalpic expansion (3-4), and isothermal heat absorption (4-1). Each stage represents a specific phase of the refrigeration cycle.

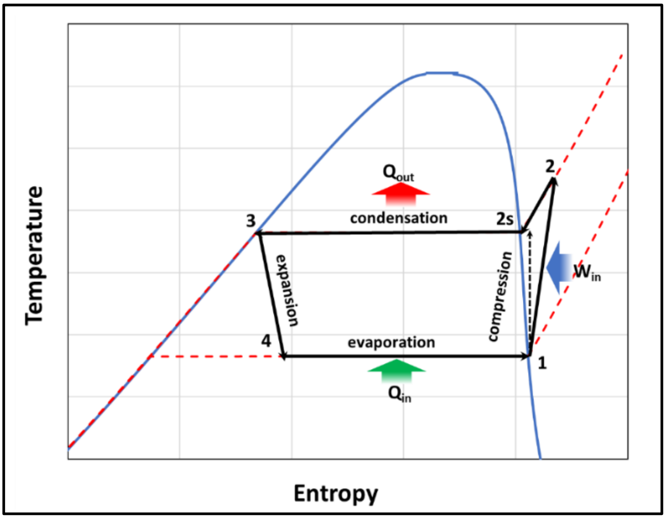

Figure 1. T-s diagram of a typical vapor compression refrigeration system

The system operates under steady-state conditions, signifying that temperature, pressure, and flow rates remain constant over time, ensuring predictable performance and simplifying thermodynamic analysis (Roberti *et al.*, 2024). Furthermore, the system is conceptualized under ideal conditions where neither superheating nor subcooling occurs during the process, ensuring that the refrigerant transitions between phases exactly at the designated temperatures. Superheating or subcooling indicates deviations from ideal phase-change behavior, which can affect system efficiency and reliability. Their absence confirms optimal operation within specified temperature ranges (Solanki *et al.*, 2023). Consequently, this operational precision ensures the refrigeration system adheres to its design specifications, maintaining the intended cooling effect and preventing deviations from standard vaporization and condensation dynamics.

In the provided schematic diagram, the 70% compressor efficiency specification, including motor efficiency, pressure drops, and heat-transfer losses, provides a comprehensive evaluation of the overall efficiency of the compression process within the refrigeration system. Compressor efficiency is a critical parameter in refrigeration systems, as it reflects how effectively electrical energy is converted into mechanical work. A higher efficiency directly correlates with reduced energy consumption and improved system performance. This 70% efficiency accounts for not only the compressor's mechanical efficiency but also factors such as motor efficiency, system pressure drops, and thermal losses during the compression phase (Song *et al.*, 2024).

2.2. Operating Condition Parameters

The temperature range for cold storage is specified as -18 to -20 °C. To achieve and maintain this range effectively, the evaporator temperature, which is where the refrigerant absorbs heat from the environment (or the contents of the cold storage), needs to be lower than the desired storage temperature. In this case, the evaporator temperature is set at -25 °C. This allows for effective heat transfer from the stored items to the refrigerant, ensuring that the contents of the cold storage remain within the desired temperature range.

The condenser temperature depends heavily on the ambient temperature, which is the temperature of the surrounding environment. To ensure the refrigeration system operates efficiently even in challenging conditions, we assume a condenser temperature of 40 °C. The condenser releases absorbed heat from the refrigerant into the ambient environment (Guo *et al.*, 2025), and its thermal performance directly affects the system's ability to maintain the desired cooling conditions. By assuming a condenser temperature of 40 °C, the system is designed to handle higher ambient temperatures, ensuring effective heat dissipation and refrigerant condensation.

The maximum cooling load of 25 kW is an assumption that takes into account various factors contributing to the total cooling load. This includes the transmission load (heat gain or loss through walls and insulation), product load (heat gain or loss from the stored products), internal load (heat generated by lights and equipment within the cold storage), infiltration load (heat entering the storage due to air exchange), and equipment load (heat generated by the refrigeration equipment itself). This assumption limits the system's capacity to ensure it can handle the combined heat loads under various operating conditions.

As fluid moves through a pipe, friction between the fluid and pipe walls leads to pressure drops, which must be minimized through careful design to maintain system efficiency (Çengel & Cimbala, 2018). A typical flow velocity in a pipe of 6 m/s is maintained to ensure a consistent pressure drop resulting from friction within the pipe. This design choice represents an optimal balance, minimizing pressure drop while effectively managing costs. It reflects a thoughtful design approach that prioritizes efficiency by minimizing friction-related energy losses while keeping overall system cost under control. Table 1 summarizes the operating parameters used in the simulation.

Table 1. Operating parameters used in the simulation

Parameter	Symbol	Value	Description
Cold storage temperature range	T_{storage}	–18 to –20 °C	Target temperature inside the storage chamber
Evaporator temperature	T_{evap}	–25 °C	Ensures effective heat transfer from stored products
Condenser temperature	T_{cond}	40 °C	Based on typical tropical ambient conditions
Maximum cooling load	$Q_{\text{load,max}}$	25 kW	Represents total heat load including transmission, product, infiltration, and internal loads

2.3. Energetic Evaluation

Compressor work is the work done by a compressor to increase a gas's pressure. It is a measure of the energy added to the gas by the compressor. The isentropic efficiency calculating the effective input energy converts into useful work to increase the pressure of refrigerant. The formula used to calculate the isentropic efficiency of a compressor is defined in Equation 1.

$$\eta_{comp} = \frac{h_2' - h_1}{h_2 - h_1} \tag{1}$$

Where h_2' is the isentropic enthalpy after compression; h_2 is the actual isentropic enthalpy after compression and it depends on the compressor's efficiency; h_1 is the enthalpy before compression.

Isentropic efficiency evaluates the performance of the compressor by measuring how effectively it compresses the refrigerant without entropy generation, indicative of ideal mechanical efficiency. Conversely, the COP quantifies the overall efficiency of the refrigeration system, defined as the ratio of the heat transfer, either absorbed from or released into the environment, to the mechanical work input to the compressor. This efficiency metric is crucial for assessing the energy efficiency of refrigeration systems, and it is mathematically articulated in Equation 2.

$$COP = \frac{\dot{Q}_{in}}{\dot{W}_{in}} = \frac{\dot{m}_{ref}\,\Delta h_{14}}{\dot{m}_{ref}\,\Delta h_{21}} = \frac{\Delta h_{14}}{\Delta h_{21}} \tag{2}$$

Where $\dot{Q}_{in}$ is the heat absorbed in evaporator; $\dot{W}_{in}$ is the compressor work; $\dot{m}_{ref}$ is the mass flow rate refrigerant; Δh_{14} is the enthalpy difference after and before evaporation process; and Δh_{21} is the enthalpy difference before and after compression. Δh_{14} is equivalent to the specific cooling load, whereas Δh_{21} represents the specific compressor work.

The formula to calculate the mass flow rate of the refrigerant is detailed in Equation 3, which is pivotal for assessing the operational performance of the refrigeration system.

$$\dot{m}_{ref} = \frac{\dot{Q}_{load}}{\Delta h_{14}} \quad (3)$$

Where $\dot{Q}_{load}$ is the cooling load.

Friction within the capillary pipe is determined by the flow rate, which refers to the volume of fluid passing through a specific cross-sectional area per unit time. To standardize the friction or pressure drop across different fluids, it is essential to adjust the cross-sectional area of the capillary pipe. This adjustment is based on the ratio of mass flow rate to density, as outlined in Equation 4. This approach ensures uniform pressure conditions within the pipe, which facilitates consistent performance across various operational scenarios.

$$\dot{V} = \frac{\dot{m}_{ref}}{\rho_{ref}} \quad (4)$$

Where V is the flow rate of refrigerant and ρ_{ref} is the density of refrigerant.

Once the flow rate of the fluid within the capillary pipe has been established, the diameter of the capillary pipe can be calculated using Equation 5:

$$d = \sqrt{\frac{4\dot{V}}{\pi\, v}} \quad (5)$$

Where d is the diameter of the capillary pipe; v is the velocity in the pipe.

Table 2 shows the basic properties of selected refrigerants used to evaluate their performance. All thermodynamic and transport properties were obtained from REFPROP v10.0 (Lemmon *et al.*, 2018).

Table 2. Basic properties of selected refrigerants (Lemmon *et al.*, 2018)

Property	Unit	Refrigerant				
		R-22	R-404a	R-134a	R-600a	R-717
Composition	-	$CHClF_2$	44% R-125/ 4% R-134a/ 52% R143a	CF_3CH_2F	C_4H_{10}	Ammonia
Molecular Weight	gr/mol	86.46	97.60	102.03	58.12	17.03
Critical Pressure	bar	49.90	37.34	40.59	36.29	113.33
Critical Temperature	°C	96.145	72.12	101.06	134.66	132.25
Normal Boiling Point	°C	-40.81	-46.22	-26.07	-11.75	-33.33
GWP	-	1810	3300	1300	<1	0
ODP	-	0.05	0	0	0	0
ASHRAE Toxicity/ Flammibility	-	A1	A1	A1	A3	B2L

3. Results and Discussions

3.1 Energetic Performances

The evaluation of energetic performance is a fundamental component of this study, as energy efficiency is a primary criterion in assessing the suitability of natural refrigerants for cold storage applications. Within the context of the vapor compression cycle model investigated, energetic indicators such as COP, compressor work, and peak pressures and temperatures rate provide quantitative measures of system efficiency under typical operating conditions. These parameters are essential for comparing the thermodynamic behavior of R-717 and R-600a and determining their capability to deliver the required cooling capacity with minimal energy losses.

3.1.1 System Efficiency

Figure 2 provides a detailed comparison of the COP for various refrigerants across a range of evaporator temperatures. Notably, R-717 consistently demonstrates the highest COP values among the listed refrigerants, indicating its exceptional efficiency in heat transfer and temperature maintenance. This superior performance extends across all evaporator temperatures, with R-717 notably surpassing others, particularly at lower temperatures such as -25 °C and -20°C. Despite its toxic nature, the remarkable efficiency of R-717 makes it an attractive option for cold chain operations where energy efficiency is paramount. However, stringent safety measures are necessary to mitigate the associated risks (Sharma *et al.*, 2025).

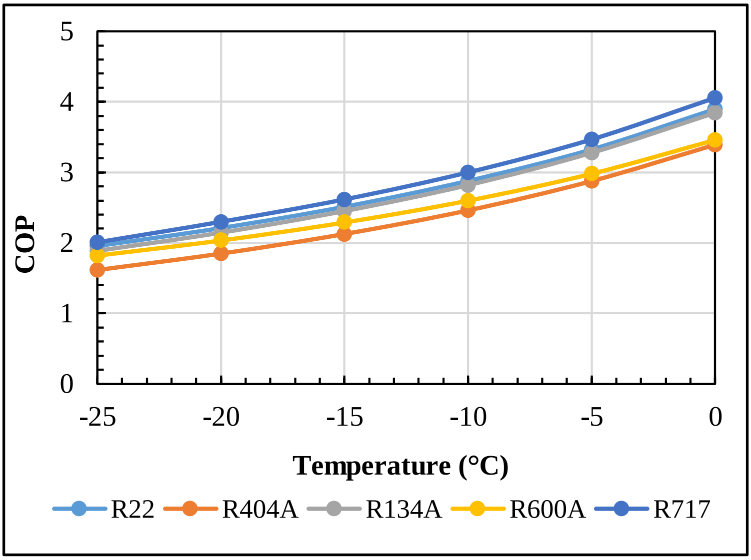

Figure 2. Comparison of COP between refrigerants in different evaporator temperatures

The superior performance of R-717 can be attributed to its favorable thermophysical properties. R-717 possesses a high latent heat of vaporization, which enhances the refrigerating effect per unit mass of refrigerant. This characteristic leads to a lower mass flow rate requirement and reduced compressor work, thereby increasing the COP. Additionally, its relatively low molecular weight and excellent thermal conductivity contribute to efficient heat transfer and improved system efficiency.

R600a demonstrates competitive thermodynamic performance across the evaluated evaporation temperature range, as illustrated in Figure 2. Although its COP remains slightly lower than that of R22, R134a, and R717, R600a consistently outperforms R404A throughout the entire temperature range, especially at lower evaporator temperatures around -25 °C. This suggests its suitability for efficiently sustaining refrigeration temperatures. While R-600a's COP values are generally lower than R-717's, its lower environmental impact positions it as a sustainable alternative, aligning with global efforts to reduce greenhouse gas emissions.

Conversely, other studied refrigerants like R-22, R-404a, and R-134a exhibit moderate to lower COP values compared to R-717 and R-600a across the temperature range. R-22, once widely used but now phased out due to its ozone-depleting properties, shows relatively lower efficiency levels. Similarly, while R-404a and R-134a are commonly used replacements for ozone-depleting refrigerants, their COP values fall short of the efficiency observed with R-717 and R-600a (Sánchez *et al.*, 2017; Soni *et al.*, 2023). Additionally, their high global warming potential raises environmental concerns. Therefore, R-717 and R-600a emerge as promising candidates for replacing other refrigerants due to their superior efficiency and lower environmental impact. However, a thorough evaluation of safety considerations, regulatory compliance, and operational requirements is essential to ensure their suitability for specific cold chain applications.

One significant factor contributing to these losses is dynamic viscosity, a property that impacts the flow characteristics of fluids. Dynamic viscosity refers to the resistance of a fluid to flow when subjected to shear stress or strain rate. Higher dynamic viscosity values indicate greater resistance to flow, which can result in increased pressure drops within the pipelines of the refrigeration system. These pressure drops, in turn, lead to energy losses and reduced overall efficiency of the system.

Figure 3 visually illustrates the relationship between dynamic viscosity and refrigerants, highlighting R-134a as having the highest dynamic viscosity among the refrigerants considered. This characteristic makes R-134a more prone to experiencing higher pressure drops and lower heat transfer performance within the system compared to other refrigerants, potentially contributing to decreased efficiency (Sharma *et al.*, 2025).

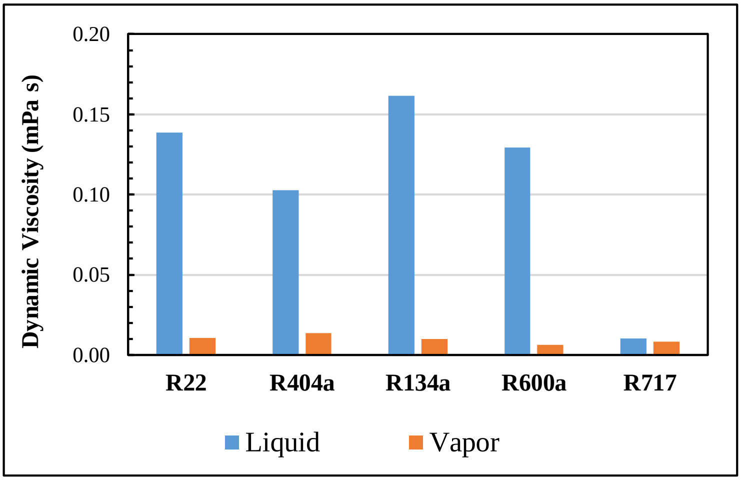

Figure 3. Dynamic viscosity of selected refrigerants at operating saturation conditions

The interaction between dynamic viscosity and refrigerant selection highlights the need to consider both COP and fluid flow characteristics when designing and optimizing refrigeration systems (Fedele *et al.*, 2023). This dual focus can optimize both efficiency and functionality.

Compressor work calculations traditionally rely on refrigerant mass flow rate, a standard metric for assessing performance. However, the compression process within the compressor occurs with respect to volume, not just mass. This distinction becomes significant when comparing the performance of the same compressor with different refrigerants.

In practical terms, the outcomes of compressor performance may deviate from theoretical calculations based solely on mass flow rate due to inherent differences in the volumetric characteristics of various (Alsouda *et al.*, 2023). Figure 4 illustrates this point by comparing volume flow rates among different refrigerants.

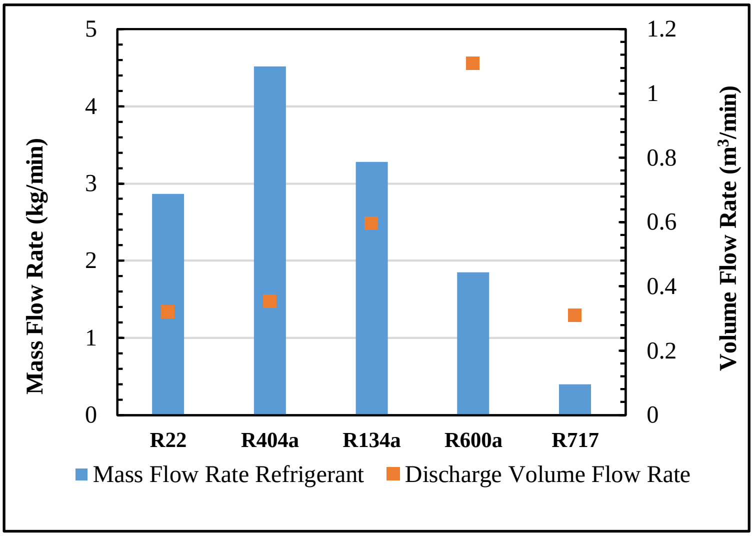

Figure 4. Compressor discharge flow rate of selected refrigerants at design conditions

The volume flow rate, or volumetric flow rate, represents the volume of refrigerant passing through a given point per unit of time. It accounts for the density of the refrigerant, which varies among different substances. Therefore, even if two refrigerants have the same mass flow rate, their volume flow rates may differ due to variations in density.

These differences in volume flow rates directly impact the compression process within the compressor. Refrigerants with higher volumetric efficiency can displace more volume per unit of time, potentially affecting compressor performance. This means that the compressor may need to work differently or at varying capacities when handling different refrigerants, even if the mass flow rates remain constant. Refrigerants might have the same mass flow rates to fulfill a particular cooling requirement, but their volume flow rates could diverge, affecting the overall cooling load. This disparity arises because compressors function according to specific volume flow rates rather than mass flow rates. This implies that to accommodate various refrigerants, either the compressor needs to be altered, or its compressor speed adjusted to handle different volume flow rates.

Understanding and accounting for these volumetric characteristics are essential for accurately predicting and optimizing compressor performance across different refrigerants. Both mass and volume flow rates can be considered to make more informed decisions when designing and operating refrigeration systems, ensuring optimal efficiency and performance.

3.1.2 Peak Temperature

During the operation of a refrigeration system, the compressor's function is crucial in elevating the pressure, consequently leading to increased temperatures in the condenser. As depicted in Figure 5, the refrigerant R-717 exhibits a notable characteristic with a peak temperature reaching as high as 150°C to achieve a saturation liquid temperature of 40°C. This significant temperature disparity poses potential risks to nearby objects since the surroundings may be exposed to high temperatures.

Similarly, R-22 displays elevated temperatures, reaching up to 74 °C. However, these temperatures are still within a range that can generally be tolerated. In contrast, refrigerants such as R-134a, R-404A, and R-600a demonstrate more favorable behavior, with peak temperatures only slightly exceeding the target condensing temperature by approximately 10 °C. This suggests a lower risk of harm to nearby objects, making these refrigerants comparatively safer in terms of temperature impacts during the condensation process.

The peak temperature observed in the condenser is a critical parameter to consider, especially operational efficiency (Guth & Atakan, 2023) and system reliability (McLinden *et al.*, 2020; Saeed *et al.*, 2023). Excessive temperatures can lead to overheating, degradation of components, and potential hazards to personnel or nearby materials. Therefore, selecting refrigerants with lower peak temperatures relative to the desired operating conditions can mitigate these risks and ensure the safe and effective operation of the refrigeration system. Additionally, proper insulation and ventilation measures should be implemented to manage heat dissipation and prevent adverse effects on the surroundings.

Furthermore, the peak temperature reached in the condenser has broader implications beyond safety concerns. It also impacts the overall efficiency and longevity of the refrigeration system. Excessive heat can accelerate wear and tear on system components, leading to increased maintenance costs and potential downtime.

In the case of R-717, the significant temperature difference required to achieve the desired saturation liquid temperature highlights a potential inefficiency in the system. Such high temperatures not only pose safety risks but also indicate a less optimized process. Optimizing the refrigerant choice and system design to minimize temperature differentials can lead to improved energy efficiency and reduced operating costs over the system's lifespan.

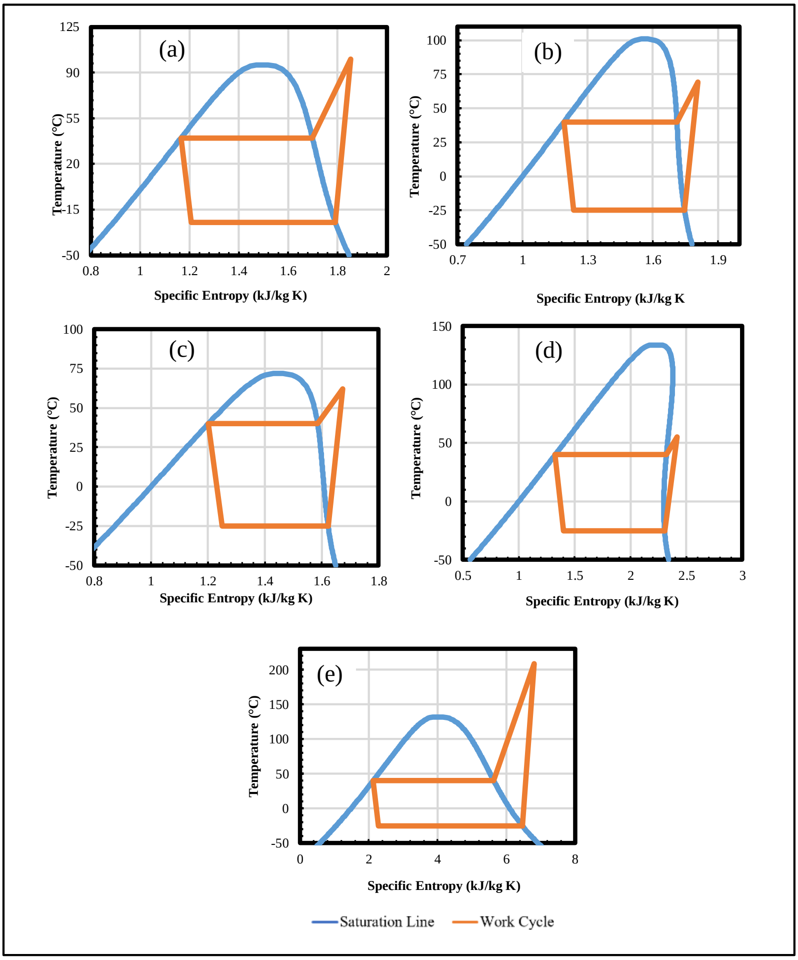

Figure 5. Work cycle of refrigerants in T-s diagram: R-22 (a), R-134a (b), R-404A (c), R-600a (d), R-717 (e)

High compressor discharge temperatures also significantly influence lubricant stability and material compatibility in vapor-compression refrigeration systems. In this study, peak temperatures approaching 150 °C were observed at the compressor outlet, which may accelerate lubricant degradation and affect compressor durability. Elevated temperatures can lead to thermal breakdown, oxidation, and viscosity reduction of lubricating oils, potentially compromising system reliability and efficiency.

The selection of appropriate lubricants is therefore essential. R-717 is typically compatible with mineral oils and alkylbenzene lubricants but incompatible with copper and copper-based alloys, necessitating the use of steel components. In contrast, hydrofluorocarbon refrigerants such as R-134a and R-404A generally require polyolester (POE) oils due to their superior miscibility and thermal stability. Similarly, hydrocarbons like R-600a exhibit good compatibility with both mineral oils and POE lubricants, offering flexibility in system design.

From a materials perspective, prolonged operation above 120 °C may accelerate wear, oxidation, and chemical degradation of seals and metallic components. Consequently, the use of high-temperature-resistant materials, proper lubricant selection, and adequate thermal management is critical to ensure safe and efficient operation. These considerations are particularly important when adopting alternative refrigerants such as R-717 and R-600a.

3.1.3 Peak Pressure

In vapor compression refrigeration systems, the processes of compression and expansion are fundamental to effective heat transfer. Compression, especially, is vital as it increases the refrigerant's pressure, allowing it to dissipate heat in the condenser with only minor variations in stored energy. The efficiency with which this compression occurs is pivotal and directly influences the overall performance of the refrigeration system.

Figure 6, which presents the Pressure-Enthalpy (P-h) diagram, provides a detailed analysis of the thermodynamic cycles for various refrigerants. Notably, R-600a is characterized by the lowest peak pressure in the cycle, peaking at a modest 5 bars after compression. This lower pressure suggests a less intensive compression process relative to its counterparts. In contrast, R-134a displays a peak pressure approximately twice that of R-600a, and several other refrigerants reach pressures that are threefold higher than that of R-600a. These pronounced variations in peak pressures highlight the significant differences in the thermodynamic and compression properties of each refrigerant.

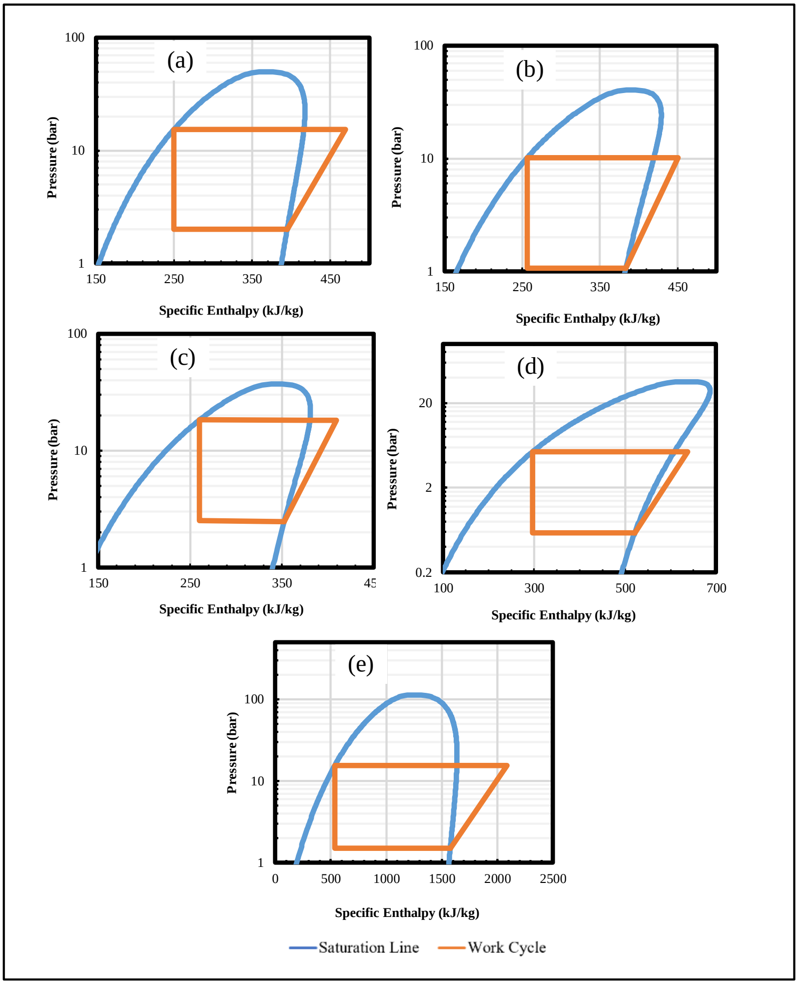

Figure 6. Work cycle of refrigerants in *P-h* diagram: R-22 (a), R-134a (b), R-404A (c), R-600a (d), R-717 (e)

The elevated pressure characteristic exhibited by certain refrigerants introduces several potential challenges and considerations for system designers and engineers. One primary concern is the risk of leakage or rupture, particularly in components such as capillary pipes, where the refrigerant experiences high-pressure differentials. Leakage not only compromises the system's efficiency (Zhang *et al.*, 2023; Zhang *et al.*, 2024) but also poses safety hazards and environmental concerns due to the release of refrigerants, many of which are potent greenhouse gases (Francis *et al.*, 2017).

To mitigate these risks, thicker pipes and more robust materials in the construction of vapor compression systems can be applied. Thicker pipes enhance the system's structural integrity, ensuring it can withstand elevated pressures without succumbing to leaks or failures. However, thicker approach comes with its own set of challenges and costs. The utilization of thicker pipes necessitates adjustments to system design, additional expenses in material procurement, and potentially increased labor costs during construction and maintenance processes.

Furthermore, the selection of a refrigerant critically affects the design and engineering strategies adopted in refrigeration systems. Refrigerants that exhibit lower peak pressures can permit the utilization of less expensive or lighter materials, potentially decreasing the total cost of the system. Conversely, refrigerants characterized by higher peak pressures necessitate the adoption of sturdier construction materials and more comprehensive safety protocols to guarantee dependable performance.

Table 3. Comparison of high pressure, low pressure, and maximum temperature of the studied working fluid

Refrigerant	Pressure Ratio	High Pressure (bar)	Low Pressure (bar)	Maximum Temperature (°C)
R22	7.61	15.34	2.01	100.52
R404a	7.39	18.29	2.48	62.12
R134a	9.55	10.17	1.06	69.08
R600a	9.09	5.31	0.58	55.48
R717	10.27	15.55	1.51	208.83

The comparative data in Table 3 highlights distinct thermodynamic characteristics of the studied refrigerants. R717 exhibits the highest pressure ratio (10.27) and maximum cycle temperature (208.83 °C), indicating strong efficiency potential for high-performance applications but also presenting challenges in terms of material compatibility and safety. R134a and R600a show relatively high pressure ratios (9.55 and 9.09, respectively) but operate at lower condenser pressures (10.17 bar and 5.31 bar), which reduces compressor discharge requirements and makes them suitable for medium- and low-capacity systems. R600a, in particular, combines low operating pressures with a modest maximum temperature (55.48 °C), aligning well with refrigeration needs where compactness and energy efficiency are prioritized. In contrast, R404a demonstrates the lowest pressure ratio (7.39) alongside the highest condenser pressure (18.29 bar), suggesting lower cycle efficiency and higher compressor load, consistent with its declining use due to environmental concerns. R22 shows balanced values across parameters, reflecting its historical popularity, though its phase-out is driven by ozone depletion potential. Overall, the analysis underscores a trade-off between efficiency, operating conditions, and environmental sustainability: R717 offers superior thermodynamic performance but requires stringent safety measures, while R600a and R134a provide environmentally favorable alternatives for household and medium-scale applications.

3.2 Environmental Impact

The international efforts spearheaded by the 1987 Montreal Protocol marked a pivotal moment in environmental conservation, particularly in safeguarding the Earth's stratospheric ozone layer from depletion (Montzka *et al.*, 2018). Recognizing the detrimental effects of ozone-depleting substances (ODS), including chlorofluorocarbons (CFCs), halons, and other compounds commonly used in refrigerants, the protocol aimed to mitigate their harmful impact on human health, ecosystems, and agricultural productivity (Bagra & Qanungo, 2025; Guggisberg & Lennan, 2025). Among the regulated refrigerants under this protocol is R-22, renowned for its cooling properties but containing chlorine, a compound known to catalyze ozone depletion (Puebla *et al.*, 2025).

The subsequent Kigali Amendment, adopted in 2016, furthered global environmental efforts by specifically targeting hydrofluorocarbons (HFCs), which, although not directly depleting the ozone layer, possess potent GWP, contributing to climate change (Wu *et al.*, 2025). This extension of the Montreal Protocol underscores the collective commitment to combat climate change by phasing down the production and consumption of HFCs on a global scale.

In line with the objectives of the Kigali Amendment, the promotion of energy-efficient technologies and practices has become paramount (Ying *et al.*, 2026). This includes advocating for the adoption of natural refrigerants such as hydrocarbons and ammonia, which offer lower or negligible GWP compared to HFCs (Ababio *et al.*, 2026). As the world seeks to transition away from environmentally harmful refrigerants, these alternatives present viable options for reducing emissions and mitigating climate change impacts.

To quantitatively evaluate their environmental performance, key indicators including Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) were analyzed, where the GWP and ODP value of studied refrigerants have been presented in Table 2. As shown in Table 2, R-717 and R-600a exhibit zero ODP and negligible GWP compared to conventional refrigerants. In contrast, R-22 contributes to ozone depletion, while R-404A and R-134a have high GWPs, making them significant contributors to global warming. These quantitative indicators confirm the environmental superiority of natural refrigerants and support their classification as sustainable alternatives.

Amidst this backdrop, R-717 and R-600a emerge as promising substitutes for R-22, R-404A, and R-134a. R-717 offers exceptional thermodynamic efficiency, zero ODP, and zero GWP, making it an attractive option for industrial refrigeration and cold chain distribution, despite its toxicity and associated safety considerations. Similarly, R-600a demonstrates excellent performance and an extremely low GWP, making it well-suited for energy-efficient refrigeration systems. However, its flammability necessitates appropriate safety measures and risk management strategies.

3.3 Safety and Design Requirements

Refrigerants are vital for the operation of refrigeration systems; however, they also present multiple risks that require meticulous management to safeguard human and environmental safety (Khudhur *et al.*, 2022; Cheekatamarla & Sharma, 2024; Huang *et al.*, 2025). While chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), and hydrochlorofluorocarbons (HCFCs) are known for their detrimental environmental impact, alternatives like hydrocarbons and ammonia introduce different safety considerations that must be addressed (McLinden, 2026).

Hydrocarbons are classified as A3 due to their high flammability, presenting an increased risk of flame, especially when utilized in refrigerated or air-conditioned transportation systems (K. Li *et al.*, 2025). This heightened risk of combustion, particularly in confined spaces where leaks or inadvertent releases of hydrocarbons can lead to the accumulation of flammable vapors, necessitates the implementation of rigorous safety measures.

To ensure the safety of refrigeration systems using hydrocarbons, a multi-faceted approach is recommended (Ibrahim *et al.*, 2025). Firstly, gas detection systems should be integrated into the system to continuously monitor hydrocarbon concentrations and detect any deviations from safe levels.

Alarms should be installed to provide timely alerts in the event of leaks, enabling swift intervention to prevent potential hazards. Emergency ventilation systems play a critical role in dispersing flammable vapors, reducing the risk of hazardous buildup. Additionally, automated fire extinguisher systems are essential for promptly suppressing fires in case of ignition, minimizing the potential for damage and injury.

Ammonia, another commonly used refrigerant, presents distinct safety challenges because it is toxic and corrosive when it contacts water or oxygen (Jaafar *et al.*, 2025). This dual hazard profile makes ammonia unsuitable for use in transportation equipment like refrigerated trucks, where managing potential emergencies can be particularly challenging. While emergency ventilation systems are typically effective at mitigating risks, their viability may be compromised when crowds are in close proximity to refrigerated trucks.

Given its toxicity, ammonia is better suited to confined spaces where access is restricted and trained personnel can carefully control the environment (Khudhur *et al.*, 2022). To counteract its corrosive effects, materials such as stainless steel are recommended for ammonia refrigeration systems. Stainless steel's corrosion resistance supports equipment longevity and safety, addressing one aspect of the complex considerations involved in using ammonia as a refrigerant.

While hydrocarbons and ammonia offer environmentally friendly alternatives to ozone-depleting refrigerants, they introduce unique safety challenges that require comprehensive risk management strategies (Khudhur *et al.*, 2022; Ibrahim *et al.*, 2025; Jaafar *et al.*, 2025). By implementing stringent safety protocols, utilizing appropriate materials and technologies, and providing thorough training for personnel, the risks associated with these refrigerants can be effectively mitigated, ensuring the safe and sustainable operation of refrigeration systems.

In this context, R-717 and R-600a emerge as promising candidates to replace other studied refrigerants, offering efficiency, environmental sustainability, and safety when managed appropriately. Their distinct characteristics present unique challenges, but with careful risk management strategies in place, they can contribute significantly to the safe and sustainable operation of refrigeration systems in cold chain distribution applications.

Table 4 presents a comprehensive comparison of selected refrigerants, shedding light on their performance across key criteria essential for cold chain distribution applications at evaporation temperature of -25 °C. Among the refrigerants studied, R-717 and R-600a emerge as particularly promising candidates to replace other studied refrigerants, offering distinct advantages and considerations.

Table 4. Performance of selected refrigerants

Criteria	Refrigerant				
	R-22	R-404a	R-134a	R-600a	R-717
COP (at Tevap= -25 °C)	1.95	1.61	1.89	1.82	2.02
Energy Losses	Medium	-	High	Medium	Low
Environmental Impact	High	High	Medium	Low	Zero
Safety	Safe	Safe	Safe	Flammable	Toxic
Requirement	-	-	-	Automated Fire Extinguisher	Confined Space

R-717 stands out with a COP of 2.02, the highest among the refrigerants listed in the table. This superior COP indicates excellent efficiency in heat transfer, making R-717 an optimal choice for maintaining desired temperatures in refrigeration systems. Additionally, R-717 exhibits low energy losses, minimizing inefficiencies during operation. However, one notable concern is its toxic nature, which requires careful handling and special considerations, particularly in confined spaces. Despite this, R-717's remarkable efficiency and low environmental impact position it as a compelling replacement for refrigerants with higher environmental footprints, such as R-22, R-404A, and R134A.

R-600a stands out as a viable alternative to other refrigerants examined in the study, displaying a COP of 1.82 and a minimal environmental footprint. This refrigerant not only provides efficient heat transfer but also contributes negligibly to ozone depletion and global warming. Due to its flammability, R-600a requires stringent safety measures, such as the integration of automated fire extinguishing systems. Nonetheless, with proper safety protocols, R-600a offers substantial benefits in terms of efficiency and environmental sustainability, making it an appealing option for replacing conventional refrigerants like R-22, R-404A, and R134A in settings where safety can be assured.

R-717 and R-600a emerge as potent alternatives to conventional refrigerants in cold chain distribution, each with distinct advantages and challenges. R-717 is highly efficient but necessitates stringent safety protocols due to its toxicity. Conversely, R-600a, while flammable, delivers robust performance and has a minimal environmental impact. By harnessing the benefits of both R-717 and R-600a and adhering to rigorous safety standards, stakeholders in the cold chain sector can improve the efficiency, sustainability, and safety of their refrigeration systems, thus fostering a greener and more resilient cold chain infrastructure.

4. Conclusions and Recommendation

This study presents a comparative thermodynamic, environmental, and safety assessment of selected refrigerants for cold storage applications. The results demonstrate that the natural refrigerants R-717 and R-600a are promising alternatives to conventional refrigerants such as R-22, R-134a, and R-404A because they combine competitive energy performance with significantly lower environmental impacts.

Among the refrigerants evaluated, R-717 achieved the highest thermodynamic performance, with a coefficient of performance of 2.02 at an evaporation temperature of −25 °C. Its superior efficiency is attributed to its favorable thermophysical properties and high latent heat of vaporization, resulting in reduced energy losses. However, R-717 also exhibited the highest compressor discharge temperature (208.83 °C) and pressure ratio (10.27), requiring robust system design, appropriate lubricant selection, and effective thermal management. In addition, its toxicity (ASHRAE Safety Class B2L) limits its application to industrial refrigeration systems equipped with proper ventilation, leak detection, and trained operators.

R-600a demonstrated a competitive COP of 1.82, outperforming R-404A while remaining slightly below R-22, R-134a, and R-717. Its relatively low operating pressure makes it suitable for compact refrigeration systems, although its high flammability (ASHRAE Safety Class A3) necessitates strict safety measures, including refrigerant charge limitations, explosion-proof electrical components, and adequate ventilation. Consequently, R-600a is particularly appropriate for small- and medium-capacity hermetically sealed refrigeration systems.

Both natural refrigerants exhibit zero ozone depletion potential and negligible global warming impact, providing clear environmental advantages over conventional refrigerants. In contrast, R-22, R-134a, and R-404A achieved COP values of 1.95, 1.89, and 1.61, respectively, but are associated with considerably higher environmental impacts due to ozone depletion or elevated global warming potential. These results highlight that refrigerant selection should balance thermodynamic performance, environmental sustainability, safety classification, and system design requirements.

Overall, R-717 is recommended for centralized industrial cold storage applications where maximum energy efficiency is required and comprehensive safety infrastructure is available. Conversely, R-600a is recommended for compact refrigeration systems that prioritize environmental sustainability while maintaining satisfactory thermodynamic performance.

Future work should focus on experimental validation, techno-economic evaluation, and life-cycle climate assessment using Total Equivalent Warming Impact (TEWI) and Life Cycle Climate Performance (LCCP). Further investigations on system optimization, refrigerant charge minimization, long-term reliability, and practical implementation will support the wider adoption of low-GWP refrigerants in sustainable cold chain refrigeration systems.

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