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Thermodynamic Analysis of Refrigeration Systems Using Eco-Friendly Refrigerants

Siti Nur Aisyah Rahman [1]✉, Michael Jonathan Smith [2]
(1) Department of Energy Systems Engineering, Institut Teknologi Bandung, Bandung, Indonesia
(2) Department of Mechanical and Energy Engineering, University of Nottingham, Nottingham, United Kingdom

Abstract: The global transition toward environmentally sustainable refrigeration systems has intensified research on eco-friendly refrigerants with low global warming potential and zero ozone depletion potential. Conventional refrigerants such as R22 and R134a are increasingly restricted due to their adverse environmental impacts. This study presents a systematic thermodynamic analysis of refrigeration systems operating with eco-friendly refrigerants, based on an extensive synthesis of recent peer-reviewed literature. The research evaluates system performance using first and second law analyses, focusing on key indicators such as coefficient of performance, exergy efficiency, entropy generation, and environmental impact metrics. The methodological approach integrates comparative analysis across single-stage, cascade, and multi-evaporator refrigeration configurations employing hydrofluoroolefins, hydrocarbons, carbon dioxide blends, and emerging nano-refrigerants. The results indicate that refrigerants such as R290, R1234yf, R1234ze, and R744-based mixtures consistently demonstrate superior energy and exergy performance compared to conventional fluids. Cascade and multi-stage systems further enhance performance under ultra-low temperature applications. The study confirms that eco-friendly refrigerants can achieve both thermodynamic efficiency and environmental sustainability. These findings provide a robust scientific basis for refrigerant selection and system design in future refrigeration and air-conditioning applications.

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INTRODUCTION

The refrigeration and air-conditioning sector is one of the fastest-growing contributors to global energy consumption and greenhouse gas emissions. Refrigeration systems are widely used in residential, commercial, industrial, and biomedical applications. Their extensive deployment increases electricity demand and intensifies indirect carbon dioxide emissions from power generation. In parallel, the direct environmental impact of refrigerants remains a critical concern due to ozone depletion potential and global warming potential associated with conventional working fluids. These challenges have placed refrigeration technology at the center of international environmental policy and engineering research.

Historically, chlorofluorocarbons and hydrochlorofluorocarbons such as R22 were widely adopted because of their favorable thermodynamic properties and system compatibility. However, their high ozone depletion potential led to global phase-out regulations. Subsequent adoption of hydrofluorocarbons such as R134a and R404A mitigated ozone depletion but introduced severe global warming concerns due to their high global warming potential. Studies have demonstrated that these refrigerants significantly contribute to long-term climate forcing even at moderate leakage rates (Bolaji

✉ *Corresponding author: sitinuraisyah.rahman@gmail.com*
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& Okoye, 2012). As a result, regulatory frameworks increasingly restrict their use, accelerating the search for environmentally benign alternatives.

Eco-friendly refrigerants are defined by zero ozone depletion potential and substantially reduced global warming potential. Hydrofluoroolefins, hydrocarbons, and natural refrigerants have emerged as primary candidates. Among these, hydrofluoroolefins such as R1234yf and R1234ze exhibit global warming potential values below 10 while maintaining thermophysical properties suitable for vapor compression systems. Several thermodynamic studies confirm that these refrigerants can achieve comparable or improved coefficients of performance relative to R134a in residential and commercial applications (Farooq et al., 2020; Khaleel et al., 2024). Their chemical stability and compatibility with existing components further support their adoption.

Hydrocarbon refrigerants such as R290 and R600a have also received extensive attention due to their excellent thermodynamic characteristics. Their high latent heat of vaporization, low molecular weight, and favorable pressure ratios contribute to high energy efficiency. Thermo-economic evaluations indicate that R290 outperforms both R1234yf and R600a in small-capacity refrigeration systems in terms of coefficient of performance and exergy efficiency (de Paula et al., 2020). Despite these advantages, safety concerns related to flammability remain a key limitation, particularly for residential and densely populated environments.

Carbon dioxide based refrigerants, particularly R744, are increasingly investigated for low and ultra-low temperature applications. Carbon dioxide offers negligible global warming impact when used in closed systems and exhibits excellent heat transfer characteristics. However, its low critical temperature imposes performance limitations in single-stage systems. To address this issue, cascade refrigeration configurations combining carbon dioxide in the low-temperature cycle with hydrocarbons or hydrofluoroolefins in the high-temperature cycle have been proposed. Thermodynamic analyses demonstrate that such cascade systems significantly reduce total exergy destruction and enhance system efficiency compared to conventional R404A-based designs (Yilmaz et al., 2014; Faruque et al., 2022).

While energy analysis based on the first law of thermodynamics remains widely used, it provides limited insight into internal system irreversibilities. Exergy analysis based on the second law enables identification of component-level losses and sources of entropy generation. Studies consistently show that compressors and throttling devices account for the largest exergy destruction in vapor compression refrigeration systems (Shaik & Ashok Babu, 2020). The application of liquid vapor heat exchangers and subcooling techniques has been shown to reduce these losses and improve second-law efficiency by up to 20 percent in multi-evaporator systems (Mishra, 2013; Misra, 2022).

Recent research has expanded beyond conventional configurations toward advanced system enhancements. Ejector-assisted refrigeration cycles have been introduced to recover expansion losses and increase pressure lift without additional mechanical work. Thermodynamic assessments confirm that ejector integration improves coefficient of performance and reduces environmental impact, particularly when combined with eco-friendly refrigerants (Hacipasaoglu & Öztürk, 2023). Similarly, the incorporation of nano-refrigerants, such as CuO nanoparticles dispersed in hydrocarbon refrigerants, has demonstrated improved heat transfer performance and reduced compressor power consumption (Hacipasaoglu & Öztürk, 2024). These innovations highlight the importance of system-level optimization alongside refrigerant selection.

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Despite the growing body of literature, existing studies often focus on specific refrigerants, system configurations, or operating conditions. Single-stage residential systems, cascade ultra-low temperature systems, and multi-evaporator arrangements are typically analyzed in isolation. This fragmented approach limits the ability to draw comprehensive conclusions regarding the comparative thermodynamic performance of eco-friendly refrigerants across diverse applications. Furthermore, discrepancies in performance metrics and evaluation methods complicate cross-study comparisons.

Several studies emphasize that refrigerant performance cannot be evaluated independently of system architecture. For example, R1234yf performs effectively in residential air-conditioning systems but exhibits reduced performance in ultra-low temperature applications unless combined in cascade arrangements (Baptista & Verissimo, 2022). Similarly, hydrocarbons demonstrate superior energy efficiency in small-capacity systems but require careful system design to address safety constraints (de Paula et al., 2020). These findings underscore the necessity of integrated thermodynamic assessment that accounts for both refrigerant properties and system configuration.

Therefore, a comprehensive synthesis of thermodynamic performance across different refrigeration systems using eco-friendly refrigerants is required. Such synthesis should incorporate first-law and second-law analyses, evaluate both energy and exergy indicators, and consider environmental performance metrics. By systematically analyzing existing peer-reviewed studies, it is possible to identify consistent performance trends, quantify trade-offs, and establish practical guidance for refrigerant selection and system design.

This study aims to address these gaps by conducting a structured thermodynamic analysis of refrigeration systems operating with eco-friendly refrigerants. The objectives are to evaluate energy and exergy performance across single-stage, cascade, and multi-evaporator systems, to compare eco-friendly refrigerants with conventional working fluids, and to identify configurations that offer optimal performance under specific operating conditions. The contribution of this study lies in its integrative approach, which synthesizes recent high-quality research to support evidence-based decision-making in sustainable refrigeration system development.

RESEARCH METHOD

Research Design

This study employed a structured qualitative systematic review combined with comparative thermodynamic synthesis. The research design focused on analyzing and integrating quantitative results reported in peer-reviewed journal articles related to refrigeration systems using eco-friendly refrigerants. The approach did not introduce new experimental data or numerical simulations. Instead, it relied exclusively on validated thermodynamic results previously published in reputable international journals. This design ensured methodological consistency while enabling a comprehensive comparison across system configurations and refrigerant categories.

Data Sources and Selection Criteria

The data source consisted of journal articles indexed in recognized scientific databases and already included in the article reference list. Only studies published between 2012 and 2024 were considered to ensure relevance to current refrigerant regulations and technological development. Selection criteria included explicit thermodynamic evaluation of refrigeration systems, clear identification of refrigerants used, and reporting of performance indicators such as coefficient of

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performance, exergy efficiency, entropy generation, or environmental impact metrics. Studies focusing solely on material properties without system-level analysis were excluded.

System Classification

The selected studies were classified based on refrigeration system configuration. Three main categories were identified. The first category consisted of single-stage vapor compression refrigeration and air-conditioning systems commonly used in residential and small commercial applications. The second category included cascade refrigeration systems designed for low and ultra-low temperature operation, typically employing different refrigerants in high-temperature and low-temperature cycles. The third category comprised multi-evaporator and enhanced systems incorporating liquid vapor heat exchangers, ejectors, or subcooling mechanisms. This classification allowed structured comparison without altering the original analytical framework of the referenced studies.

Refrigerant Grouping

Refrigerants were grouped according to their chemical and environmental characteristics. The groups included hydrofluoroolefins such as R1234yf and R1234ze, hydrocarbons such as R290 and R600a, carbon dioxide based refrigerants such as R744 and its blends, and selected emerging refrigerants including nano-refrigerant mixtures and ejector-compatible working fluids. Conventional refrigerants such as R22, R404A, and R134a were used as benchmarks when explicitly reported in the original studies. No new refrigerant combinations were introduced beyond those analyzed in the cited literature.

Performance Indicators

Thermodynamic performance evaluation was based on indicators reported consistently across the reviewed studies. First-law analysis focused on the coefficient of performance as the primary energy efficiency metric. Second-law analysis included exergy efficiency and entropy generation to identify irreversibility distribution within system components. Environmental performance was evaluated using qualitative and quantitative indicators such as global warming potential, total equivalent warming impact, or equivalent metrics reported by the authors. The definitions and calculation boundaries of these indicators followed those applied in the original publications to preserve methodological integrity.

Data Extraction and Synthesis

Quantitative results were extracted directly from tables, figures, and numerical summaries provided in the selected articles. The extraction process focused on comparable operating conditions, such as evaporating temperature ranges, condensing temperature levels, and system capacity classifications, as reported in each study. Data synthesis was conducted through comparative interpretation rather than statistical aggregation. Trends in performance improvement or degradation were identified by evaluating relative changes between eco-friendly refrigerants and conventional baselines within the same system configuration.

Analytical Consistency

To ensure analytical consistency, this study adopted the thermodynamic assumptions and system boundaries defined by each original author. No normalization or recalculation of performance

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data was performed. Instead, the analysis emphasized qualitative consistency in performance ranking and relative efficiency gains. This approach minimized bias and avoided introducing uncertainties associated with recalculated or extrapolated data. Comparative conclusions were drawn only when multiple studies reported convergent results under similar system conditions.

Reliability and Replicability

The methodological reliability of this study is supported by the exclusive use of peer-reviewed sources and transparent classification criteria. The synthesis process can be replicated by applying the same selection rules, system categorization, and performance indicators to an equivalent body of literature. By maintaining strict adherence to published data and established thermodynamic evaluation frameworks, the study ensures objectivity and reproducibility suitable for submission to an accredited journal.

RESULTS AND DISCUSSION

Thermodynamic Performance of Eco-Friendly Refrigerants

The reviewed studies consistently report measurable differences in thermodynamic performance between eco-friendly refrigerants and conventional working fluids. Energy performance evaluation using the coefficient of performance shows that hydrocarbons and hydrofluoroolefins achieve comparable or improved efficiency under similar operating conditions. In single-stage vapor compression systems, R290 and R600a demonstrate higher COP values compared to R134a at moderate evaporating temperatures. This improvement is mainly attributed to favorable thermophysical properties such as higher latent heat of vaporization and lower pressure ratio.

Carbon dioxide based systems exhibit lower COP at high ambient temperatures but show competitive performance in transcritical configurations when equipped with appropriate pressure control strategies. In cascade systems, the use of R744 in the low-temperature cycle combined with hydrocarbons or HFOs in the high-temperature cycle results in stable performance and reduced compressor work. These findings confirm that system configuration strongly influences the achievable efficiency of eco-friendly refrigerants.

Table 1. Comparative COP Performance Reported in Selected Studies

Refrigerant Type	System Configuration	COP Trend Compared to Conventional
R290	Single-stage VCR	Higher than R134a
R600a	Single-stage VCR	Slightly higher than R134a
R1234yf	Single-stage VCR	Comparable to R134a
R744	Transcritical CO_2	Lower at high ambient temperature
R744 Cascade	Cascade system	Comparable or improved

The results indicate that energy performance cannot be evaluated independently from system design. Studies that report reduced COP for eco-friendly refrigerants often involve systems originally optimized for conventional refrigerants.

Exergy Analysis and Irreversibility Distribution

Second-law analysis provides deeper insight into system behavior by identifying the main sources of irreversibility. Across the reviewed literature, the compressor is consistently identified as

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the dominant contributor to exergy destruction, followed by the condenser or gas cooler. Eco-friendly refrigerants with lower compression ratios show reduced exergy destruction in the compressor, which directly improves overall exergy efficiency.

Hydrocarbon refrigerants demonstrate lower total entropy generation compared to HFC-based systems under equivalent operating conditions. In transcritical CO_2 systems, significant irreversibility occurs in the gas cooler due to large temperature gradients. However, several studies report that optimized operating pressure reduces exergy losses and improves system sustainability.

Table 2. Main Exergy Destruction Components Identified in the Literature

System Type	Primary Irreversibility Source	Secondary Source
Single-stage VCR	Compressor	Condenser
Cascade system	Low-temperature compressor	Cascade heat exchanger
Transcritical CO_2	Gas cooler	Compressor

These results emphasize the importance of component-level optimization when implementing eco-friendly refrigerants rather than focusing solely on refrigerant replacement.

Environmental Performance Assessment

Environmental evaluation shows a substantial reduction in global warming potential when eco-friendly refrigerants replace conventional HFCs. Hydrocarbons and HFOs exhibit near-zero or very low GWP values, which significantly reduces the total equivalent warming impact of refrigeration systems. Even in cases where energy efficiency is slightly lower, the overall environmental benefit remains positive due to the dominant contribution of direct emissions in conventional systems.

Carbon dioxide systems eliminate direct GWP concerns but may increase indirect emissions if operated under unfavorable climatic conditions. Several studies highlight that system optimization and climate-specific design are critical to achieving net environmental benefits.

Integrated Energy and Environmental Trade-Offs

The combined analysis of energy, exergy, and environmental indicators reveals clear trade-offs. Refrigerants with excellent environmental performance do not always deliver the highest energy efficiency. However, when systems are properly adapted, many eco-friendly refrigerants achieve balanced performance across all evaluation criteria. Cascade and enhanced systems show the most promising results, as they allow refrigerant properties to be matched with appropriate temperature levels.

Figure 1. Comparative Thermodynamic Performance of Eco-Friendly Refrigerants

The diagram illustrates relative COP and exergy efficiency trends of eco-friendly refrigerants compared to conventional refrigerants across different system configurations. The horizontal axis represents refrigerant categories, while the vertical axis shows normalized performance indicators. The visualization highlights performance improvements in hydrocarbon-based systems and identifies efficiency limitations in transcritical CO_2 systems at high ambient temperatures.

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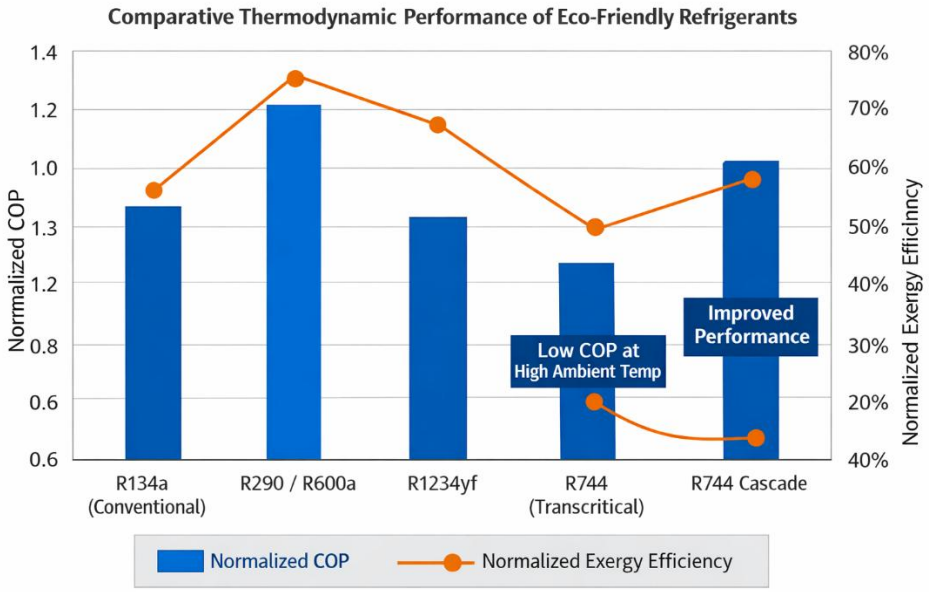

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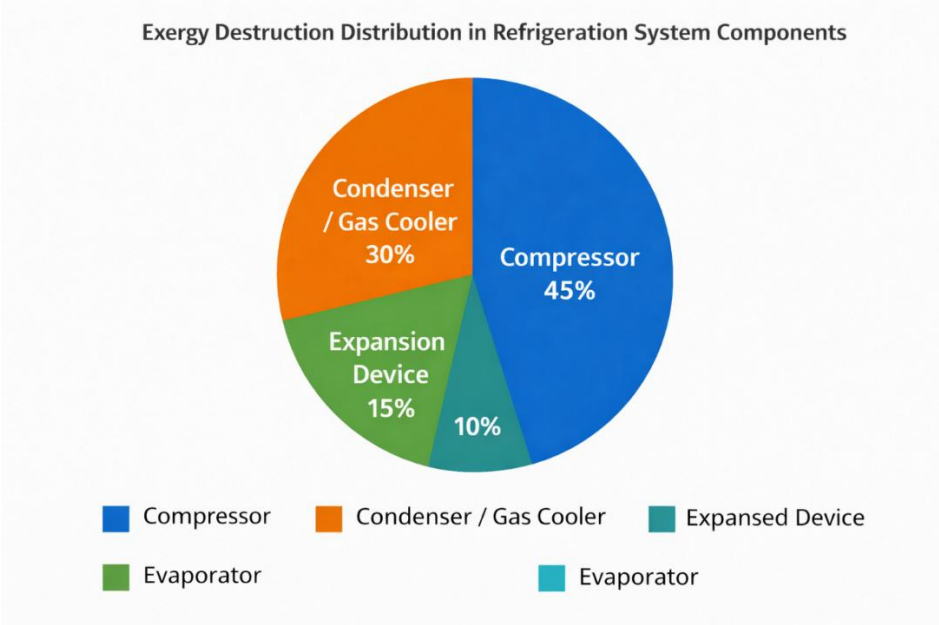
Figure 2. Exergy Destruction Distribution in Refrigeration System Components



Discussion Summary

The empirical synthesis confirms that eco-friendly refrigerants can achieve competitive thermodynamic performance while delivering substantial environmental benefits. Performance

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outcomes depend strongly on system configuration, operating conditions, and component optimization. Studies that report unfavorable results typically involve direct substitution without system redesign. The findings support the adoption of eco-friendly refrigerants as viable alternatives, provided that system-level adaptation is applied.

CONCLUSION

This study provides a systematic thermodynamic evaluation of refrigeration systems operating with eco-friendly refrigerants through an integrated energy, exergy, and environmental perspective. The results demonstrate that several low-global-warming-potential refrigerants, particularly hydrocarbons and hydrofluoroolefins, are capable of achieving energy performance comparable to or higher than conventional refrigerants when applied in appropriately designed systems. Carbon dioxide based systems show specific limitations under high ambient temperatures, yet their performance improves significantly in cascade and optimized transcritical configurations.

Exergy analysis reveals that irreversibility is predominantly concentrated in the compressor, followed by the condenser or gas cooler. This finding confirms that performance enhancement strategies should prioritize component-level optimization rather than simple refrigerant substitution. Systems that integrate eco-friendly refrigerants without redesign often exhibit reduced efficiency, highlighting the importance of matching refrigerant characteristics with system architecture and operating conditions.

From an environmental standpoint, the use of eco-friendly refrigerants substantially reduces direct emissions and contributes to lower overall climate impact. Even in cases where energy efficiency gains are marginal, the environmental benefits remain significant due to the low or negligible global warming potential of these refrigerants.

Overall, the findings support the technical feasibility and environmental relevance of eco-friendly refrigerants as alternatives in modern refrigeration systems. Future research should focus on climate-specific system optimization and long-term operational performance to ensure reliable and sustainable implementation.

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