International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 10 Issue: 10 | Oct - 2026 SJIF Rating: 8.659 ISSN: 2582-3930

A Critical Review of Thermodynamic Performance, Exergy Efficiency, Environmental Sustainability and Refrigerant Replacement Strategies in Vapour Compression Refrigeration Systems

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Abstract - The transition from conventional high-global-warming-potential (GWP) refrigerants toward environmentally sustainable alternatives has become too essential for reducing the impact on environmental for refrigeration and air-conditioning systems. R134a has been widely used in vapour compression refrigeration (VCRs) systems because of its favourable thermodynamic properties, chemical stability and reliable stable operating system performance. This review paper critically examines the thermodynamic performance, exergy efficiency, environmental sustainability and replacement strategies associated with R134a-based VCR systems. The performance characteristics of potential alternatives, including R600a, R152a, R290, R1234yf, R1234ze(E), R513A and other low GWP refrigerants, are comparatively evaluated. Key parameters such as coefficient of performance (COP) refrigeration capacity, compressor power, mass flow rate, pressure ratio and exergy destruction are systematically discussed. The review further examines the effects of evaporating temperature, condensing temperature, refrigerant charge, superheating, subcooling and system configuration on overall performance. Environmental indicators including GWP, ozone depletion potential (ODP) total equivalent warming impact (TEWI) and life-cycle climate performance (LCCP) are also considered. Particular consideration is given to the trade-off between thermodynamic performance, environmental impact, safety, component compatibility and modify feasibility. The review identifies key research gaps related to standardized experimental comparison, multi-objective optimization and integrated energy–exergy–environmental impact. Finally, future research directions are proposed for developing high efficiency, low GWP, safe and sustainable refrigeration systems as alternatives to R134a.

Key Words: refrigerant, performance R134a, Low GWP Refrigerants, Vapour Compression Refrigeration System (VCRS), Thermodynamic Performance, Exergy Analysis, Environmental Sustainability, Performance Optimization, Refrigerant Replacement.

1.INTRODUCTION

Vapour Compression Refrigeration Systems (VCRS) are widely used for domestic refrigeration, air conditioning, food preservation and industrial cooling applications. The performance of a VCRS mainly depends on the thermodynamic properties of the refrigerant, operating conditions and the design of major components such as the compressor, condenser, expansion device and evaporator.

R134a (1,1,1,2-tetrafluoroethane) has been extensively used in VCRS particularly in domestic refrigerators and automotive air-conditioning systems, due to its favorable thermodynamic properties, chemical stability, non-corrosive nature and compatibility with commonly used refrigeration components and lubricants. In a conventional R134a refrigeration cycle, the refrigerant undergoes compression, condensation, expansion and evaporation to provide the required cooling effect.

The increasing concern regarding climate change, however, has highlighted the environmental limitations of R134a because of its relatively high global warming potential (GWP). Although R134a has zero ozone depletion potential (ODP) its high GWP has encouraged the refrigeration industry and researchers to investigate alternative low GWP refrigerants.

Therefore, considerable research has focused on evaluating alternatives refrigerant such as R600a, R152a, R290, R1234yf and R1234ze(E). The selection of an appropriate replacement requires simultaneous consideration of coefficient of performance (COP), cooling capacity, compressor power consumption, exergy, system efficiency, impact on environment, system safety, refrigerant flammability and component compatibility.

Consequently, R134a remains an important base refrigerant for evaluating the thermodynamic and environmental performance of emerging low GWP refrigerants. A critical assessment of R134a-based VCRS is essential for understanding its performance characteristics and establishing suitable path toward more energy-efficient and environmentally sustainable refrigeration systems.

2. Review of Previous Research

M. M. Joybari, M. S. Hatamipour et al. [1] (2013): investigated the exergy performance and optimization of R600a as a replacement for R134a in a domestic refrigerator. The study found that the compressor was the major source of exergy destruction, followed by the condenser, capillary tube and evaporator. Using Taguchi optimization, the optimum R600a charge was reported as 50 g compared with 145 g of R134a, representing a substantial reduction in refrigerant charge. The study demonstrated that R600a can provide a promising low GWP alternative while simultaneously reducing refrigerant charge and environmental risk. This study established an important relationship between refrigerant charge, exergy destruction and optimization, providing a foundation for subsequent R600a research.

Bolaji and co-workers [2] (2010): investigated R152a as an alternative refrigerant for domestic refrigeration applications. Their experimental results indicated that R152a could achieve comparable or improved COP relative to R134a, while offering a substantially lower environmental impact. However, the flammability of R152a was identified as an important limitation for direct application. This work demonstrated that refrigerant selection requires a balance between thermodynamic performance and safety considerations. The study highlighted the importance of evaluating performance together with refrigerant safety, rather than relying only on COP.

M. Rasti, S. F. Aghamiri et al. [3] (2013): numerically investigated R152a, R1234yf and R1234ze(E) as low GWP alternatives to R134a in a vapour compression refrigeration system. The analysis showed that R152a could provide a higher COP than R134a under the investigated conditions, while R1234yf and R1234ze(E) provided environmentally attractive alternatives. The study demonstrated that low GWP refrigerants can exhibit different thermodynamic behavior even when they are considered substitutes for the same baseline refrigerant. The study supports the need for simultaneous thermodynamic and environmental assessment of replacement refrigerants.

R. Cabello, D. Sánchez et al. [4] (2015): performed energy and exergy analyses of different refrigerants in vapour compression refrigeration systems. Their results indicated that R152a could achieve higher exergy efficiency and lower exergy destruction than R134a under the investigated conditions. The study emphasized that refrigerant evaluation based only on first-law efficiency may overlook important losses occurring within individual system components. This research strengthened the argument for incorporating second-law/exergy analysis into refrigerant-selection studies.

D. Sánchez, R. Cabello et al. [5] (2016): experimentally investigated R152a as a drop-in replacement for R134a in a domestic refrigeration system. The study evaluated operating performance and refrigerant charge under comparable conditions. R152a demonstrated favorable thermodynamic characteristics and was identified as a potential alternative, although its flammability remains a critical consideration. The research showed that replacement feasibility depends not only on refrigerant properties but also on system configuration and charge level. This study is particularly relevant to drop-in replacement strategies.

J. M. Belman-Flores, A. P. Rodríguez-Muñoz et al. [6] (2017): experimentally compared R134a with R152a, R1234yf, R1234ze(E) R600a and R290 using the same refrigeration facility and operating conditions. R290 showed increased COP and cooling capacity, while R152a and R1234yf produced relatively small variations compared with R134a. In contrast, R600a and R1234ze(E) showed reductions in cooling capacity and COP under the investigated conditions.

The study importantly demonstrated that the performance of a replacement refrigerant is highly dependent on the operating conditions and system configuration. This is one of the key comparative studies for your review because several low GWP refrigerants were evaluated under common conditions.

J. M. Belman-Flores, V. H. Rangel-Hernández et al. [7] (2017): A further experimental investigation evaluated R152a as a drop-in replacement for R134a in a domestic no-frost refrigerator. Pull-down and 24-hour energy-consumption tests were conducted to assess the practical replacement potential. The study reported that R152a has similar normal boiling and critical temperatures to R134a, while providing a major reduction in GWP. However, its higher flammability requires appropriate safety considerations. The paper confirms that thermodynamic similarity does not automatically imply unrestricted drop in compatibility.

A. Maiorino, C. Aprea et al. [8] (2018): further demonstrated the importance of optimization when replacing R134a with R600a. Their experimental work showed that refrigerant charge was the most influential parameter among the investigated optimization variables. The optimized R600a system achieved a substantially lower total exergy destruction than the baseline configuration. The research indicates that R600a performance should be evaluated using optimized operating conditions, rather than simply replacing R134a at the same charge.

R. V. Hernández, J. M. Belman-Flores et al. [9] (2022): experimentally compared R152a and R134a in an oil-free domestic refrigeration system. R152a achieved an average COP/EER approximately 26% higher than R134a and showed lower total exergy destruction. The study reported approximately 7% higher exergy efficiency for R152a.

However, the researchers emphasized that flammability remains an important barrier to conventional domestic applications. This paper provides strong evidence that low GWP alternatives can simultaneously improve first-law and second-law performance, although safety must be considered.

A. Maiorino, R. Llopis et al. [10] (2022): experimentally evaluated R513A, R1234yf and R436A as alternatives to R134a in a cascade refrigeration system using R744. The study investigated cooling capacity and system operating conditions and demonstrated the applicability of low GWP refrigerants in more complex refrigeration configurations. This work expands the discussion beyond conventional single stage VCR systems and demonstrates the importance of application-specific refrigerant selection.

X. Chen, K. Liang, Z. Li et al. [11] (2022): A review by researchers investigating R1234yf examined strategies for improving the performance of R1234yf-based VCR systems. The review considered internal heat exchangers, ejectors, refrigerant-charge optimization, component optimization, nano-lubricants and refrigerant mixtures. The authors highlighted that although R1234yf provides a very low GWP option, its thermodynamic and flammability characteristics require system-level improvements. This research demonstrates that replacement of R134a may require system modification rather than simple refrigerant substitution.

M. Z. Sharif, W. A. Wan Hamzah et al. [12] (2023): reviewed the development of ultra-low GWP working fluids for small-capacity vapour compression systems. The review examined refrigerants including hydrocarbons and low GWP HFC/HFO alternatives and emphasized the importance of balancing thermodynamic performance, environmental impact and safety. The authors also discussed experimental evidence for R152a, R600a and other alternatives. This study establishes the broader transition from high-GWP HFCs toward ultra-low GWP refrigerants.

J. Wang, P. Gullo et al. [13] (2024): Recent research has increasingly moved from simple refrigerant substitution toward integrated system optimization, including alternative cycle configurations, advanced heat exchangers and hybrid technologies. The literature indicates that the performance of a refrigerant can change considerably when system architecture is modified.
Therefore, future studies need to evaluate refrigerant selection together with compressor characteristics, heat-exchanger design, expansion devices and operating parameters. This trend supports the need for system-level assessment rather than refrigerant-property comparison alone.

A. M. Ashour, S. A. Kadhim et al. [14] (2025): Experimentally investigated R152a, R513A, R290, R1234yf and R600a in a VCR system integrated with thermoelectric subcooling. Under the investigated conditions, R152a increased

COP by 12.3%, while R513A increased cooling capacity by 23.5%. R290 also showed a COP improvement, whereas R600a provided moderate benefits. The study demonstrates that combining low GWP refrigerants with performance-enhancement techniques can improve system efficiency. This represents a shift from simple replacement toward refrigerant + system enhancement strategies.

R. Cabello, D. Sánchez et al. [15] (2017): Recent research increasingly focuses on multi-objective assessment rather than selecting a refrigerant based on a single parameter such as COP or GWP. The current literature indicates that a suitable R134a replacement should simultaneously provide acceptable cooling capacity, low compressor power, high COP and exergy efficiency, low GWP, low total environmental impact, acceptable safety characteristics and compatibility with refrigeration components. Consequently, R600a, R152a, R290, R1234yf, R1234ze(E) and R513A each offer different advantages and limitations depending on the application and operating conditions. Recent experimental work confirms that no single refrigerant can be considered universally optimal.

This provides the basis for the central argument of the present review: R134a replacement should be treated as a multi-criteria optimization problem rather than a simple refrigerant substitution problem.

3. Review of Previous Research

Although numerous studies have investigated individual R134a alternatives, direct comparison under identical experimental conditions remains relatively limited and many studies evaluate only COP or cooling capacity without integrating energy, exergy, environmental impact, safety and optimization. The results for R600a, R152a and other alternatives also vary with refrigerant charge, evaporating and condensing temperatures, compressor characteristics and heat-exchanger configuration.

Therefore, your review can establish the need for a standardized and integrated assessment framework for R134a and low GWP alternatives, with particular emphasis on R600a as a potential replacement in domestic VCR systems.

3. Review of Previous Research

3.1 Refrigerant Generation

Since 1830-1930 was the first generation of refrigerants. It was based on the availability. These refrigerants were more highly toxic, flammable and some very highly reactive in nature. Examples include Ethers, CO etc. . Since 1930- 1990 was the second generation of refrigerants, was focused on reducing toxicity and flammability. Example: CFCs, HCFCs, HFCs, NH3, HO etc. Since 1990-2010 was the third generation of refrigerants, was focused on protecting the ozone layer. Example - HCFCs, HFCs, HCs, NH3, H2O, CO2 etc . Since 2010 to onwards be the fourth generation is being focusing on refrigerants that do not contribute to global warming, ozone layer depletion, efficient, non-flammable and non-toxic with good stability. But the outlook for discovery or synthesis of these ideal refrigerants is extremely unlikely. Therefore, trade-off among desired objectives is necessary to achieve the balanced solution

Tabel-1: Some properties of selected alternative refrigerants

Refrigerant	Chemical	Molecular Weight	Freezing Point	Boiling	ODP	GWP (100-year)
R134a	$C_2H_2F_4$	102.03	−103.3	−26.1	0	1430
R152a	$C_2H_4F_2$	66.05	−118.6	−24.0	0	124–138
Ammonia (R717)	NH_3	17.03	−77.7	−33.3	0	≈ 0
HFO-1234yf	$C_3H_2F_4$	114.04	≈ −152	−29.5	0	1–4
CO_2 (R744)	CO_2	44.01	−56.6*	−78.5*	0	1
R600a (Isobutane)	C_4H_{10}	58.12	−159.4	−11.7	0	≈ 3
R32	CH_2F_2	52.02	−136.8	−51.7	0	675–677

**Note: For CO_2, −56.6°C is the triple-point temperature; at atmospheric pressure, CO_2 sublimes at approximately −78.5°C rather than boiling. GWP values vary with the assessment source and reporting standard.*

3.2 Research gaps identified from previous studies

The literature summarized and indicates that considerable research has been conducted on replacing R134a with low GWP refrigerants however, the reported performance varies significantly with operating conditions, refrigerant charge, compressor characteristics and system configuration. Most studies have focused on individual performance indicators such as COP, cooling capacity or GWP, while comparatively fewer studies have integrated energy, exergy, environmental and safety parameters under comparable experimental conditions. This observation highlights the need for a comprehensive assessment framework for selecting suitable R134a alternatives based on thermodynamic performance, exergy efficiency, environmental sustainability and practical replacement feasibility.

3.3 Critical Research Gap

Based on the above summarized literature, it can be observed that substantial research has been conducted on replacing R134a with low GWP refrigerants such as R600a, R152a, R290, R1234yf. However, reported results vary considerably because of differences in refrigerant charge, compressor, evaporating and condensing temperatures, heat-exchanger design, expansion device configuration and experimental methodology.

Most previous investigations have focused primarily on COP, cooling capacity and GWP, while relatively fewer studies have simultaneously considered energy performance, exergy efficiency, environmental impact, safety and replacement feasibility. Furthermore, the use of performance-enhancement technologies such as IHX, thermoelectric subcooling and ejectors is generally investigated independently of refrigerant selection.

Therefore, there is a need for an integrated and standardized evaluation framework in which R134a and low GWP alternatives are compared under comparable operating conditions using energy, exergy, environmental, safety and optimization criteria. Such an approach can provide a more reliable basis for identifying the most suitable refrigerant and operating conditions for sustainable vapour compression refrigeration systems.

3. Conclusion

The approach from R134a to low GWP refrigerants is essential for improving the environmental sustainability of vapour compression refrigeration systems. This review shows that alternatives such as R600a, R152a, R290, R1234yf and can provide competitive or improved thermodynamic performance compared with R134a under suitable operating conditions. R600a and R152a are particularly promising for high efficiency refrigerants, while R290 offers excellent thermodynamic performance with very low GWP. Exergy analysis provides additional insight into component wise irreversibility's and helps identify major sources of performance degradation. The overall suitability of a refrigerant depends not only on COP and cooling capacity but also on GWP, TEWI/LCCP, flammability, safety, compatibility and modification feasibility. Performance-enhancement techniques such as charge optimization, internal heat exchangers, thermodynamic subcooling and advanced optimization methods can further improve system performance. However, variations in system configuration, refrigerant charge, operating conditions and experimental methods make direct comparison among published studies difficult. Future research should therefore integrate energy, exergy, environmental, safety and economic assessments through multi-objective optimization and experimental validation. Overall, the systematic replacement of R134a with suitable low GWP refrigerants can support the development of efficient, environmentally sustainable and reliable next-generation refrigeration systems.

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