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Article

A comprehensive optimization and energy conservation assessment of R1234yf-based hybrid nanorefrigerants for sustainable HVAC applications: Thermodynamic, economic, environmental and AI

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Abstract: In this study, authors present a complete energy system optimization framework of R1234yf based hybrid nanorefrigerant and hybrid nanolubricant system for improving the thermodynamic, economic, environmental and energy performance of vapor compression refrigeration system for Indian operating conditions. Six nano-particles (Al_2O_3, TiO_2, CuO, SiO_2, graphene nanoplatelets (GNP) and multi-walled carbon nanotubes (MWCNT)) were assessed for the thermophysical parameters, dispersion stability, coefficient of performance (COP) of the system, exergy efficiency, energy consumption of the compressor, life-cycle economics, environmental impact, and artificial intelligence-based prediction. The results show that the thermal conductivities of nanorefrigerants are significantly better than those of the conventional refrigerants, and the COP of the R1234yf system is improved closer to the COP of the conventional refrigerants, with the Al_2O_3–SiO_2/PAG hybrid nanolubricant being more stable, while also reducing the power consumption of the compressor and improving the exergy efficiency. Both economic analysis and environmental assessment show good payback periods and significant reductions in indirect carbon emissions. The energy optimization of the system can be performed quickly and accurately with high reliability using the artificial neural network models. The proposed hybrid nanorefrigerant approach not only enables energy conservation and sustainable cooling but also paved a way for the HVAC systems to be compatible with renewable energy resources and to become low-carbon refrigeration technologies, directly contributing to Sustainable Development Goal 7 (Affordable and Clean Energy) via its high energy efficiency and its contribution to cooling in an environmentally friendly way.

Keywords: energy system optimization; energy conservation; sustainable HVAC; hybrid nanorefrigerants; SDG (Sustainable Development Goal) 7; process innovation

1. Introduction

Cooling technologies are one of the fastest growing end use energy sectors globally and heating, ventilation and air-conditioning (HVAC) systems have contributed to a significant increase in energy demand due to rapid growth of global energy demand, urbanization, and climate change. Today, around 30–40% of the world's electricity use is in buildings, and refrigeration and air-conditioning systems are a significant portion of this demand, especially in the tropical and subtropical regions. Therefore, enhancing the energy efficiency of the vapor compression refrigeration systems has become an imperative goal to reduce the electricity consumption, minimize operational costs, avoid greenhouse gas emissions and facilitate the transition towards sustainable and low carbon energy systems. The Paris Agreement and the United Nations Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), rely on technological innovation, as well as the use of energy-efficient HVAC solutions. This shift to evaporating refrigerants with a low global warming potential (GWP) and environmental alternatives has become an integral part of refrigeration policy around the world. This is due to the excellent thermodynamic properties and operational reliability of conventional hydrofluorocarbons (HFCs) like R134a. Their high GWP has however been a point of concern and strict regulations in international treaties, such as the Kigali Amendment to the Montreal Protocol, have been put in place to promote the use of low-GWP refrigerants. Since then, R1234yf has come out as one of the most promising hydrofluoroolefin (HFO) refrigerants, thanks to its ultra-low GWP and zero ozone depletion potential. However, a decrease in cooling capacity, coefficient of performance (COP) and volumetric refrigeration capacity have been reported in previous investigations when R1234yf was used without system optimization, especially in high ambient temperature conditions like those in India.

To address these challenges, nanotechnology has gained a considerable interest as an effective method to enhance the performance of refrigeration system. By adding nanoparticles to refrigerants or compressor lubricants, the thermal conductivity of refrigerants will be improved, the boiling and condensation heat transfer will be improved, the friction of the compressor will be reduced, and the efficiency of the whole system can be improved. It has been shown recently that metal oxide nanoparticles, carbon-based nanomaterials and hybrid metal oxide-carbon based nanocrystals can significantly enhance the thermophysical and tribological performance of refrigeration systems. In particular, hybrid nanolubricants, which combine the properties of several nanoparticles, offer an attractive route for the improvement of system performance and energy efficiency due to their superior thermal transport property, dispersion stability, wear reduction and compressor power consumption reduction.

Many studies have been conducted on nanorefrigerants containing R1234yf, but there still exist some important research gaps. Although numerous studies are dedicated to single nanoparticles or to single thermodynamic performance indicators, there are only limited studies that integrate energy analysis, exergy analysis, environmental assessment, economic assessment, and optimization using artificial intelligence. Moreover, very few studies have been conducted on the performance and operational cost of refrigeration systems with the use of hybrid nanolubricants in the Indian climatic conditions, where the ambient temperature is high and the electricity cost is high, which significantly affect the operational performance and life of refrigeration systems. Studies published previously have also given a few insights into the application of nanorefrigerants for energy saving, renewable energy utilization, and sustainable HVAC design.

To this end, the present study puts forth a comprehensive framework for the assessment of R1234yf based hybrid nanorefrigerants and hybrid nanolubricants that encompasses thermodynamic analysis, energy and exergy assessment, environmental impact evaluation, economic feasibility analysis and artificial intelligence based performance prediction. Six types of nanoparticles, namely Al_2O_3, TiO_2, CuO, SiO_2, graphene nanoplatelets and multi-walled carbon nanotubes (MWCNTs), are systematically tested to study their effect on thermophysical properties, refrigeration performance, compressor energy consumption, and system efficiency. The proposed framework goes beyond the traditional refrigerant assessment and positions hybrid nanorefrigerants as a viable strategy for optimizing the energy system, which can benefit SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), and improve the sustainable cooling technologies, while contributing to the SDG 13 goal of making energy compatible with renewable energies.

The next generation of refrigerants that are available include R1234yf, which has an ultra-low GWP value of less than one and zero ozone depletion potential. Recent research [1] has shown that R1234yf can have a significant impact on direct GHG emissions when used in place of R134a in refrigeration and air-conditioning applications. In a few investigations, however, it has been reported that R1234yf has been used directly in existing vapor compression refrigeration systems without performance enhancement strategies, but has been found to reduce the cooling capacity, coefficient of performance (COP), and volumetric cooling capacity. Pipwala et al. [2] carried out research work on the direct-cooled refrigerator with CuO-R600a as a nanorefrigerant and found that the, nanorefrigerant has great potential in the field of refrigeration system. In the same way, research on the retrofit of low-GWP refrigerant systems has revealed higher compressor operating power consumption and lower thermodynamic efficiency in high ambient operating conditions [3, 4]. Such constraints are more important in developing tropical countries like India where ambient temperature is often above 40°C and cooling demand is increasing rapidly.

To address the thermodynamic limitations of low-GWP refrigerants, nanotechnology-based enhancement techniques have attracted considerable research attention. The dispersion of nanoparticles into refrigerants or compressor lubricants has been recognized as an effective method for improving thermal conductivity, enhancing heat transfer coefficients, reducing compressor friction losses, and increasing overall refrigeration system efficiency [5]. Comprehensive reviews on nanorefrigerants have indicated that metal oxide nanoparticles such as Al_2O_3, TiO_2, and CuO can significantly improve the thermophysical properties of refrigeration fluids while maintaining acceptable operational stability [6, 7]. Studies demonstrated that nanoparticle-enhanced refrigerants improve heat transfer characteristics and reduce energy consumption in vapor compression systems [8], while others reported notable improvements in thermal conductivity and system performance through CuO-based nanorefrigerants [9,10].

With regard to the research trends, the research from mono-nanoparticle formulations to hybrid nanorefrigerants and hybrid nanolubricants has been shifted, because of their superior thermal transport characteristics and synergistic behavior. Hybrid nanoparticles systems have the ability to combine the benefits of each individual type of nanomaterials, so that thermal conductivity, suspension stability and tribology properties can be enhanced at the same time. Al_2O_3-SiO_2 hybrid nanolubricants were investigated by Sharif et al. [11] in air-conditioning systems using R1234yf, and found that considerable improvement in COP and compressor performance was obtainable. Yıldız [12] mentioned that combining nanoparticles with refrigerants can result in significant thermophysical enhancements in R1234yf systems. Zawawi et al. [13] have shown that binary nanolubricants with TiO_2 and SiO_2 nanoparticles can increase the COP, decrease the exergy destruction, and improve the environmental performance of the vapor compression refrigeration systems.

More recently, the incorporation of artificial intelligence and machine learning methods in modeling and optimization of refrigeration systems have been highlighted. In recent years, ANN-based predictive models have indicated a great potential to accurately predict cooling capacity, compressor power consumption, exergy efficiency and refrigeration performance with little testing [14]. Experiments testing the prediction accuracy of R1234yf/nanoparticle mixtures have been reported to be greater than 98% accurate [15] and intelligent modeling approaches can dramatically decrease the cost and time to evaluate performance. These methods are especially useful in developing countries where there are few large-scale experimental facilities available.

Although there have been many publications addressing R1234yf nanorefrigerants and nanolubricants, there are still issues that need to be addressed. First, most of the published work is targeted towards individual nanoparticles, such as Al_2O_3, TiO_2 or CuO, while investigations of hybrid combinations of nanoparticles are rather limited [16–18]. Second, the works done to date are mostly based on thermodynamic performance parameters like COP and cooling capacity, and in-depth studies that combine energy, exergy, environmental and economic parameters are limited [19, 20]. Thirdly, although hybrid nanorefrigerants are of great significance for application in industry, few studies have investigated the practical economic feasibility of their use by performing payback period analysis [21, 22]. Also, very scant studies have been performed under the Indian climatic and economic conditions in which HVAC systems are rapidly growing and high ambient temperatures and rising electricity tariffs have a significant effect on the performance of refrigeration systems and its life cycle cost [23].

Another emerging concern is the environmental concerns related to degradation products from hydrofluoroolefin. R1234yf has minimal direct GWP but recent studies have raised the possible risk of the formation of trifluoroacetic acid (TFA) in the atmosphere [24, 25] and concerns around per- and polyfluoroalkyl substances (PFAS) arising from fluorochemical manufacturing processes. Therefore, only direct GWP reduction measures are not enough and considering wider environmental impacts is important to assure long-term sustainability of low-GWP refrigerants.

Therefore, the aim of the present study is to develop a comprehensive evaluation framework of R1234yf-based hybrid nanorefrigerants and nanolubricants, which combines the thermodynamic, environmental and economic performance analysis. The Al_2O_3, TiO_2, CuO, SiO_2, graphene, and carbon nanotubes (CNTs) are systematically examined and their effects on thermophysical properties, refrigeration performance, exergy efficiency, and energy consumption of compressor are discussed. Further, a payback period modelling and environmental impact assessment study is also included to understand the practical deployment feasibility in India. Artificial neural network models are developed as well for quick performance prediction of refrigeration systems under different operating conditions. The results of this study would be useful in identifying a complete pathway for improving the performance of low GWP refrigeration systems and the sustainable development of HVAC systems in developing nations like India.

2. Literature review

Wang et al. [26] have studied the ultra-low GWP working fluids for vapor-compression systems and found that environment is not the only criterion for future refrigerant selection, and that the other criteria are energy performance, safety and cost. The charging process for R1234yf, R152a and R134a in automotive thermal management loops has been investigated by Kang et al. [27] and it was found that the cooling capacity and power consumption are significantly dependent on the optimum amount of charge. In the study of Höges et al. [28], R1234yf and hydrocarbon refrigerants were evaluated experimentally in a brine-water heat pump, showing that R1234yf can be technically viable, but needs optimization of the system level to ensure that it is competitive. Albà et al. [29] studied the sustainable design of cooling cycles with low-GWP refrigerants, highlighting the importance of optimizing both cycle architecture and low-GWP refrigerant to realize practical performance benefits. Pektezel and Ozdemir [30] optimized the R290 and R1234yf vapor compression refrigeration systems with respect to their performance parameters COP and compressor work, and they concluded that the evaporator and condenser temperatures have a significant effect on those performance parameters.

In a heat-pump air-conditioning system for electric vehicles, Lei et al. [31] studied the energy behavior of the refrigerants R1234yf, R152a and R744, noting that exergy destruction due to compressor irreversibility is the most significant one. Butt et al. [32] studied the energy, exergy, and life-cycle climate performance of low-GWP refrigerants in cascade refrigeration systems, and concluded that both direct and indirect emission indicators need to be considered for refrigerant replacement. Arefin et al. [33] studied cascade refrigeration systems with low-GWP refrigerants, such as R1234yf and R1234ze(E), and found that the choice of pairing of the high and low temperature circuits significantly affects the system performance. Chaturvedi et al. [34] discussed exergy losses in vapor compression refrigeration system and verified that exergy efficiency, total exergy loss, COP and compressor power are important parameters for comparative study of refrigerants in the vapor compression refrigeration system. Deharkar et al. [35] conducted the advanced exergy analysis of vapor compression systems and found that the selection of the expansion device and the distribution of irreversibilities of the components have a significant impact on relative performance of R1234yf and R134a. Ashour et al. [36] explored energy, exergy and environmental performance of low-GWP refrigerants for vapor-compression air conditioning system and emphasized on integrated sustainability assessment for refrigerant transition.

Bibin and Gundabattini [37] examined the density of Al_2O_3/R1234yf, TiO_2/R1234yf, and CuO/R1234yf nanorefrigerants and reported that density variation is a critical parameter because it affects Reynolds number, friction factor, pressure drop, and refrigerant charge requirement. Tomassetti et al. [38] investigated the dynamic viscosity of low-GWP refrigerants in the liquid phase and developed correlations useful for modeling pressure drop and heat transfer in HFO-based systems. Xing and Zhai [39] investigated TiO_2/R141b nanorefrigerant properties and showed that nanorefrigerants can enhance thermodynamic performance in low-temperature energy systems through improved stability and thermal behavior. Gouse and Omprakash [40] studied the performances of refrigeration using nano-additive lubricants and found that the thermophysical properties of the refrigerant-lubricants mixture are enhanced by the nanoparticles and thus enhance the cooling performances. Kumar et al. [41] experimentally investigated flow condensation of R123/MWCNT nanorefrigerant inside a horizontal tube. MWCNT addition enhanced the condensation heat-transfer coefficient, with the maximum improvement reaching 29% at 0.1% nanoparticle concentration and 400 kg/m²s mass velocity. The authors also developed a correlation predicting condensation heat transfer with acceptable accuracy. Kumar et al. [42] experimentally investigated the frictional pressure drop of R123-MWCNT nanorefrigerant during flow condensation in a horizontal tube. Increasing MWCNT concentration increased pressure drop, while higher saturation temperature reduced it. Zhang et al. [43] experimentally measured the thermal conductivity of nanorefrigerants at low nanoparticle volume concentrations and developed predictive models to correlate thermal conductivity with operating parameters. The study demonstrated that nanoparticle addition can improve thermal conductivity, highlighting the potential of nanorefrigerants for enhanced heat-transfer performance in refrigeration and thermal-energy applications. Alawi and Sidik [44] investigated the influence of nanoparticle concentration and temperature on the thermophysical properties of CuO/R134a nanorefrigerant. The results showed that increasing CuO concentration enhanced thermal conductivity and viscosity, while temperature significantly affected these properties. Alawi and Sidik [45] developed mathematical correlations to predict the thermal conductivity and dynamic viscosity of nanorefrigerants based on nanoparticle concentration, temperature, and other influencing parameters. Kosmadakis and Neofytou [46] investigated the effects of nanorefrigerants on heat-pump performance and economic feasibility. Their analysis showed that nanorefrigerants can enhance heat-transfer characteristics and improve system performance under suitable operating conditions.

The literature reviewed supports that R1234yf is a good candidate solution to replace the existing aforementioned refrigerants, but it may cause performance penalties when used directly in the traditional applications. Recent studies have also demonstrated that nanorefrigerant and nanolubricant can have an impact on the thermal conductivity, compressor behaviour, COP, and energy efficiency. Yet, most of the available literature focuses on either thermodynamic assessment or performance of individual nanoparticles. There are very few studies which incorporate energy, exergy, environmental and economic assessment for R1234yf based hybrid nanorefrigerants in Indian HVAC operating conditions. Hence, the present study aims at filling this gap and develops a combined thermodynamic, environmental and payback-period evaluation framework for R1234yf hybrid nanorefrigerants.

Novelty and contribution

Although the development of low-GWP refrigerants and nanotechnology-based cooling systems has made great strides, there is still not a broad-based evaluation framework that can incorporate thermodynamic performance, energy efficiency, exergy analysis, environmental sustainability, economic feasibility and intelligent prediction. Previous studies have investigated individual nanoparticles or single energy system performance metrics, but not how these interact to optimize overall energy systems and sustainable HVAC applications. Moreover, scientific studies on the hybrid nanolubricants at Indian operating conditions which include ambient and high temperatures with a higher cooling demand are limited. Based on the above, this study suggests a comprehensive framework in evaluating R1234yf-based hybrid nanorefrigerants and hybrid nanolubricants that combines thermophysical property analysis, refrigeration performance evaluation, energy and exergy analysis, environmental impact analysis, economic analysis, and prediction using artificial intelligence. The research also places hybrid nanorefrigerants in the landscape of enabling technologies for energy savings, HVAC systems that are compatible with renewable energy sources, and low carbon cooling systems.

The major research contributions of this study are summarized as follows:

1. A comprehensive thermodynamic, energy, exergy, environmental, economic, and artificial intelligence-based evaluation framework for R1234yf-based hybrid nanorefrigerants is developed.
2. The influence of six nanoparticle systems (Al_2O_3, TiO_2, CuO, SiO_2, graphene nanoplatelets, and multi-walled carbon nanotubes) on the thermophysical properties and refrigeration performance of R1234yf is systematically investigated.
3. Hybrid nanolubricants are evaluated as a strategy to reduce compressor power consumption, improve coefficient of performance (COP), and enhance exergy efficiency under Indian climatic conditions.
4. Artificial neural network (ANN) models are developed to accurately predict refrigeration system performance, providing a rapid optimization tool for sustainable HVAC system design.
5. Economic feasibility is assessed using discounted payback period analysis, while environmental performance is quantified through reductions in direct and indirect greenhouse gas emissions.
6. The study demonstrates the potential of hybrid nanorefrigerants for energy system optimization, renewable-energy-compatible cooling technologies, and sustainable HVAC applications.

3. Materials and methods

In this study, a multi-stage method was used to estimate the performance of the R1234yf-based hybrid nanorefrigerants and hybrid nanolubricants from the thermodynamic, energy, environmental, economic, and artificial intelligence perspectives, for sustainable HVAC systems. In the proposed framework, Nanorefrigerant preparation, characterization of thermophysical properties, experimental performance evaluation, energy and exergy analyses, environmental impact assessment, economic feasibility analysis and prediction using artificial neural network (ANN) have been combined in a single energy system optimization method. The methodology aimed to identify formulations of nanoparticles that would help increase the refrigeration performance while decreasing the energy consumption of compressors, greenhouse gas emissions, and compatibility of vapor compression refrigeration systems with renewable-energy-driven HVAC applications. The overall research methodology is presented in a schematic form in **Figure 1**.

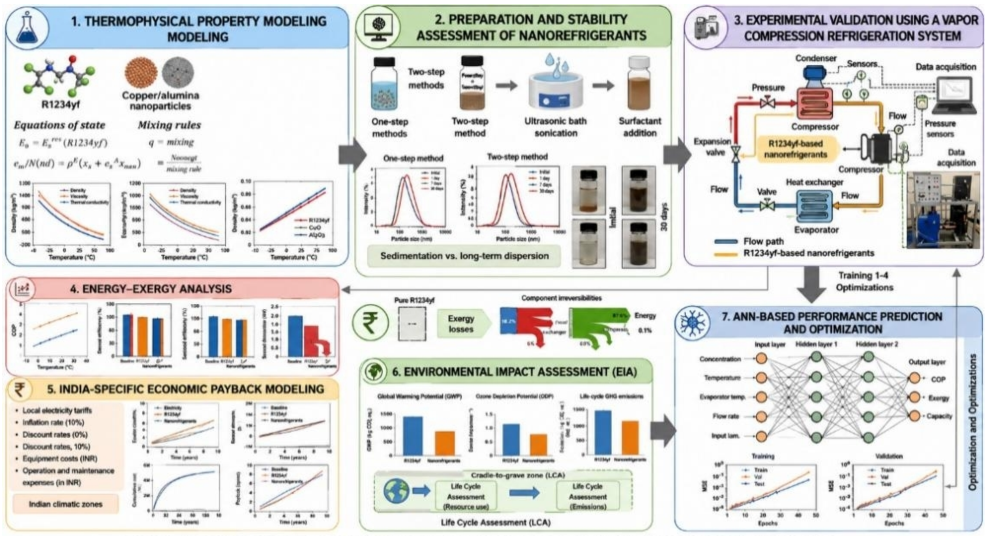


Figure 1. Proposed research framework for R1234yf-based hybrid nanorefrigerant performance evaluation.

3.1. Research framework

In the current study, a multi-stage methodological approach was used to assess the technical, environmental and economic feasibility of using R1234yf-based hybrid nanorefrigerants for HVAC applications. The framework incorporated five key stages; namely thermophysical property modelling, preparation and stability assessment of nanorefrigerants, experimental validation of a vapour compression refrigeration system, energy–exergy analysis, modelling for economic payback in India and environmental impact assessment, and prediction of the system performance using ANN.

3.2. Materials selection and nanorefrigerant preparation

The nanoparticles chosen are metal oxide and carbon-based nanoparticles with complementary thermophysical and tribological properties. Their joint assessment allows for systematic comparison of traditional and novel nanoparticle systems for improving the energy efficiency of R1234yf refrigeration systems.

R1234yf was chosen as a base refrigerant because it is a refrigerant with ultra-low GWP and zero ODP, and is suitable to be used as an alternative refrigerant to R134a in low- and medium-capacity cooling systems. In the study, a number of different types of nanoparticles were taken into consideration: Al_2O_3, TiO_2, CuO, SiO_2, graphene nanoplatelets and multi-walled carbon nanotubes (MWCNTs). The thermal conductivity, density, form, availability, and compatibility with refrigeration systems were taken into account when choosing these nanoparticles (see **Table 1**).

Table 1. Specifications of nanoparticles used for R1234yf-based nanorefrigerant preparation.

Nanoparticle	Average size	Purity (%)	Shape	Thermal conductivity (W/m·K)	Density (g/cm^3)
Al_2O_3	30–50 nm	99.8	Spherical	40	3.95
TiO_2	20–40 nm	99.5	Spherical	8.4	4.23
CuO	30–50 nm	99.9	Nearly spherical	76.5	6.31
SiO_2	15–25 nm	99.5	Spherical	1.4	2.20
Graphene nanoplatelets	2–8 nm thick, 5–10 µm lateral	99	Platelet	~5,000	2.20
MWCNT	10–20 nm OD, 10–30 µm length	95	Tubular	~3,000	2.10

The nanorefrigerants were prepared using a two-step dispersion method. Initially, nanoparticles were dried in a vacuum oven at 105 °C for 24 h to remove moisture. The required nanoparticle mass was then measured using a high-precision analytical balance. R1234yf was charged into an evacuated stainless-steel mixing vessel, followed by the addition of nanoparticles at selected volume concentrations. Dispersion was carried out using an ultrasonic processor operating at 20 kHz and 750 W for 45 min at 40% amplitude. An ice bath was used during sonication to prevent temperature rise and minimize refrigerant property variation. No surfactant was added in order to avoid alteration of thermophysical properties. Mono-nanoparticle samples were prepared at 0.2%, 0.4%, 0.6%, 0.8%, and 1.0% volume concentrations. Binary hybrid nanorefrigerants were prepared at a total concentration of 0.5% with nanoparticle ratios of 25:75, 50:50, and 75:25. For nanolubricant-based evaluation, Al_2O_3-SiO_2/PAG samples were prepared at 0.01%, 0.03%, and 0.05% volume concentrations (see **Table 2**).

Table 2. Experimental concentration matrix used in the study.

Sample type	Nanoparticle system	Concentration range
Mono nanorefrigerant	Al_2O_3, TiO_2, CuO, SiO_2, graphene, MWCNT	0.2–1.0 vol.%
Hybrid nanorefrigerant	Al_2O_3–SiO_2, CuO–CNT, graphene–metal oxide	0.5 vol.% total
Hybrid nanolubricant	Al_2O_3–SiO_2/PAG	0.01–0.05 vol.%

3.3. Stability assessment

The stability of prepared nanorefrigerants and nanolubricants was evaluated using sedimentation observation, zeta potential measurement, dynamic light scattering (DLS), and UV-Vis spectrophotometry. Sedimentation photographs were captured at 24 h intervals for 30 days to visually monitor particle settling, as shown in **Figure 2**, section A. Zeta potential was measured using a Malvern Zetasizer Nano ZS, where an absolute zeta potential value greater than 30 mV was considered acceptable for physical stability (**Figure 2**, section B). DLS was used to observe particle size distribution and agglomeration tendency over time (**Figure 2**, section C). UV-Vis absorbance measurements were conducted at characteristic wavelengths of 215 nm for Al_2O_3, 325 nm for TiO_2, 295 nm for CuO, and 270 nm for graphene.

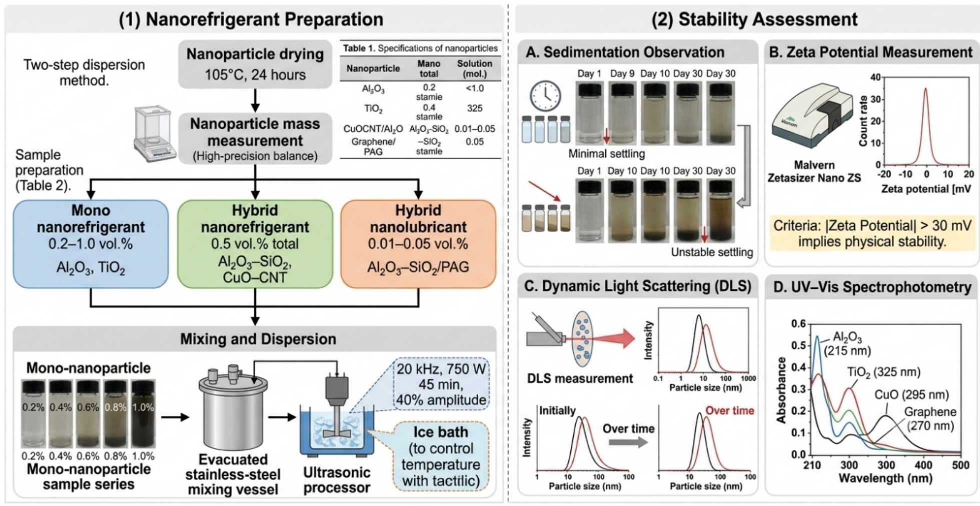


Figure 2. Nanorefrigerant preparation and stability assessment procedure.

3.4. Thermophysical property characterization

The major thermophysical properties evaluated in this study included density, thermal conductivity, viscosity, and specific heat capacity. The properties of pure R1234yf were obtained from REFPROP 10.0 for the temperature range of 273–323 K. Nanorefrigerant properties were estimated using established mixture models and validated against available experimental data. The density of nanorefrigerant was calculated using the Pak and Cho model:

$$\rho_{nf} = (1 - \phi_v)\,\rho_{bf} + \phi_v \rho_p \tag{1}$$

where ρ_{nf} is the density of nanorefrigerant, ρ_{bf} is the density of base refrigerant, ρ_p is nanoparticle density, and ϕ_v is the nanoparticle volume concentration. Thermal conductivity was estimated using the Maxwell model with particle shape correction:

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + (n-1)k_{bf} - (n-1)\phi_v(k_{bf} - k_p)}{k_p + (n-1)k_{bf} + \phi_v(k_{bf} - k_p)} \tag{2}$$

where k_{nf}, k_{bf}, and k_p represent the thermal conductivity of nanorefrigerant, base refrigerant, and nanoparticle, respectively. The shape factor n was taken as 3 for spherical particles and 6 for cylindrical particles.

The viscosity of nanorefrigerant was estimated using the Brinkman model:

$$\mu_{nf} = \mu_{bf}(1 - \phi_v)^{-2.5} \tag{3}$$

The specific heat capacity was calculated using the thermal equilibrium model:

$$c_{p,nf} = \frac{(1 - \phi_v)\rho_{bf} c_{p,bf} + \phi_v \rho_p c_{p,p}}{\rho_{nf}} \tag{4}$$

For binary hybrid nanorefrigerants, the density was calculated as:

$$\rho_{hnf} = (1 - \phi_{v1} - \phi_{v2})\,\rho_{bf} + \phi_{v1}\rho_{p1} + \phi_{v2}\rho_{p2} \tag{5}$$

The effective thermal conductivity of the hybrid nanoparticle phase was estimated using a weighted average approach:

$$k_{hp} = \frac{k_{p1}\phi_{v1} + k_{p2}\phi_{v2}}{\phi_{v1} + \phi_{v2}} \tag{6}$$

3.5. Experimental test rig configuration

The experimental validation was conducted using a vapor compression refrigeration system retrofitted from R134a to R1234yf. The test rig consisted of a hermetic reciprocating compressor, air-cooled fin-and-tube condenser, thermostatic expansion valve, and brazed plate evaporator. The baseline system used pure R1234yf with PAG46 lubricant, while the test configurations used R1234yf with selected nanorefrigerants and hybrid nanolubricants (see **Table 3**).

Table 3. Specifications of the vapor compression refrigeration test rig.

Component	Specification
Compressor	Hermetic reciprocating compressor
Cooling capacity	1.5 TR/5.28 kW
Condenser	Air-cooled fin-and-tube condenser
Condenser area	12.5 m^2
Evaporator	Brazed plate heat exchanger
Evaporator area	3.2 m^2
Expansion device	Thermostatic expansion valve
Lubricant	PAG46 and DEC PAG nanolubricant
Refrigerant charge	650 ± 10 g
Base refrigerant	R1234yf

T-type thermocouples, piezoresistive pressure transmitters, a Coriolis mass flow meter, a digital power analyzer and a data acquisition system were all installed on the test rig. The temperature at the compressor inlet and outlet, condenser inlet/outlet, evaporator inlet/outlet and the compression valve inlet/outlet were measured. Pressure readings were taken at the four significant points of the refrigeration cycle. The power of compressor was measured by a digital power analyzer and the mass flow rate of refrigerant was measured by a Coriolis flow meter (see **Table 4**).

Table 4. Instrumentation details and measurement accuracy.

Parameter	Instrument	Accuracy
Temperature	T-type thermocouple	±0.2 °C
Pressure	Piezoresistive pressure transmitter	±0.25% FS
Mass flow rate	Coriolis flow meter	±0.10%
Power consumption	Digital power analyzer	±0.1%
Data acquisition	NI cDAQ system	1 Hz sampling

Experiments were carried out at evaporator temperatures of 0 °C, 5 °C and 10 °C and condenser temperatures of 45 °C, 50 °C and 55 °C which are considered as high ambient operating conditions in India. The subcooling and superheating were kept at 5 K. The ambient temperature was fixed at 35 °C in a controlled chamber. Data were sampled at a frequency of 1 Hz and then averaged over 10 min of steady-state operation (see **Figure 3**).

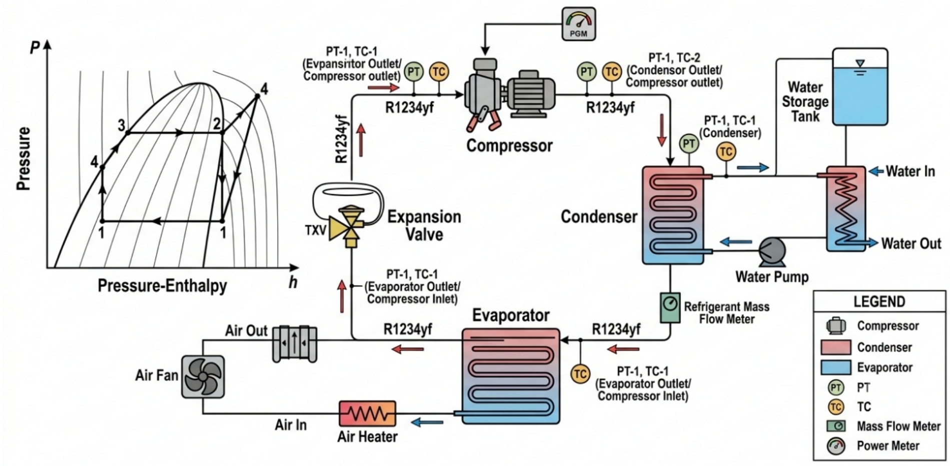


Figure 3. Schematic diagram of the R1234yf vapor compression refrigeration test rig.

3.6. Energy analysis

The energy performance of the system was evaluated using cooling capacity, compressor power, coefficient of performance, and volumetric cooling capacity. The evaporator cooling capacity was calculated as:

$$\dot{Q}_{evap} = \dot{m}_r\,(h_1 - h_4) \tag{7}$$

The compressor work input was calculated as:

$$\dot{W}_{comp} = \frac{\dot{m}_r(h_2 - h_1)}{\eta_{motor}} \tag{8}$$

The coefficient of performance was determined as:

$$COP = \frac{\dot{Q}_{evap}}{\dot{W}_{comp}} \tag{9}$$

The volumetric cooling capacity was calculated using:

$$VCC = \rho_{suction}\,(h_1 - h_4) \tag{10}$$

where $\dot{m}_r$ is the refrigerant mass flow rate, h_1, h_2, and h_4 are specific enthalpies at respective cycle points, η_{motor} is motor efficiency, and $\rho_{suction}$ is suction vapor density.

3.7. Exergy analysis

Exergy analysis was carried out to identify irreversibility in each component of the vapor compression refrigeration system. The reference dead state was taken as $T_0 = 35$ °C or 308.15 K and $P_0 = 101.325$ kPa.

The exergy destruction in the compressor was calculated as:

$$\dot{E}_{xdest,comp} = \dot{m}_r T_0\,(s_2 - s_1) \tag{11}$$

The exergy destruction in the condenser was calculated as:

$$\dot{E}_{xdest,cond} = \dot{m}_r \left[(h_2 - h_3) - T_0 \left(s_2 - s_3 \right) \right] \tag{12}$$

The exergy destruction in the expansion valve was calculated as:

$$\dot{E}_{xdest,TXV} = \dot{m}_r T_0 \left(s_4 - s_3 \right) \tag{13}$$

The exergy destruction in the evaporator was calculated as:

$$\dot{E}_{xdest,evap} = \dot{m}_r [(h_1 - h_4) - T_0(s_1 - s_4)] - \dot{Q}_{evap} \left(1 - \frac{T_0}{T_{evap}} \right) \tag{14}$$

The total exergy destruction was calculated as:

$$\dot{E}_{xdest,total} = \sum \dot{E}_{xdest,i} \tag{15}$$

The exergy efficiency was determined as:

$$\eta_{ex} = \frac{\dot{Q}_{evap} \left(1 - \frac{T_0}{T_{evap}} \right)}{\dot{W}_{comp}} \tag{16}$$

3.8. Economic payback period modeling

An India-specific economic model was developed to evaluate the feasibility of adopting R1234yf-based nanorefrigerants and hybrid nanolubricants. The model included nanoparticle cost, preparation cost, retrofit cost, additional refrigerant inventory cost, operating cost savings, and maintenance cost variation.

The total capital cost was calculated as:

$$C_{capital} = C_{nanoparticles} + C_{preparation} + C_{retrofit} + C_{inventory} \tag{17}$$

The annual operating cost savings were calculated as:

$$\Delta C_{operating} = (\dot{W}_{comp,baseline} - \dot{W}_{comp,nano}) \times H_{annual} \times E_{tariff} \times (1+\alpha)^n \tag{18}$$

The maintenance cost difference was expressed as:

$$\Delta C_{maintenance} = C_{maintenance,nano} - C_{maintenance,baseline} \tag{19}$$

The simple payback period was calculated as:

$$SPB = \frac{C_{capital}}{\Delta C_{operating} - \Delta C_{maintenance}} \tag{20}$$

The discounted payback period was calculated using:

$$\sum_{t=1}^{DPB} \frac{\Delta C_{operating,t} - \Delta C_{maintenance,t}}{(1+r)^t} = C_{capital} \tag{21}$$

where H_{annual} is annual operating time, E_{tariff} is electricity tariff, α is annual tariff escalation rate, r is discount rate, and n is the year of analysis (see **Table 5**).

Table 5. Economic parameters used for Indian payback analysis.

Parameter	Value/Range
Residential AC operating hours	1,600 h/year
Commercial AC operating hours	3,000 h/year
Automotive AC operating hours	1,200 h/year
Annual tariff escalation	5.2%
Discount rate	12%
Skilled labor rate	₹250–400/h
Carbon credit value	₹1,800–2,500/tCO_2e
Exchange rate	₹83.5/USD
Import duty assumption	18% GST + 10% customs duty

3.9. Environmental impact assessment

The environmental assessment considered direct refrigerant emission reduction, indirect emission reduction due to compressor energy savings, TFA formation potential, and PFAS-related manufacturing concerns.

The direct GWP reduction was calculated as:

$$\Delta GWP_{direct} = (GWP_{R134a} m_{R134a} L_{annual}) - (GWP_{R1234yf} m_{R1234yf} L_{annual}) \quad (22)$$

The indirect emission reduction was calculated as:

$$\Delta GWP_{indirect} = (\Delta \dot{W}_{comp} \times H_{annual}) \times EF_{grid,India} \quad (23)$$

where $EF_{grid,India}$ was taken as 0.72 tCO_2/MWh.

The *TFA* formation potential was estimated as:

$$M_{TFA} = m_{R1234yf,released} \times f_{TFA,yield} \quad (24)$$

where $f_{TFA,yield}$ was considered in the range of 0.95–1.0 based on atmospheric oxidation assumptions. PFAS release was evaluated qualitatively based on refrigerant manufacturing source transparency and environmental control practices.

3.10. Artificial neural network development

Artificial neural network models were developed to predict COP, exergy efficiency, isentropic efficiency, and total exergy destruction. A dataset of 450 data points was generated from the validated numerical model, covering all nanoparticle types, concentrations, temperature conditions, and operating parameters. The dataset was divided into 70% training, 15% validation, and 15% testing subsets.

Two multilayer perceptron models were considered:

- ANN Model 1: 10 input parameters (evaporator inlet temperature, evaporator outlet temperature, condenser inlet temperature, condenser outlet temperature, compressor suction pressure, compressor discharge pressure, refrigerant mass flow rate, nanoparticle type, nanoparticle concentration, and ambient temperature) for design-stage prediction.
- ANN Model 2: 8 input parameters (evaporating temperature, condensing

temperature, subcooling, superheating, compressor power, nanoparticle type, nanoparticle concentration, and cooling capacity) for operational monitoring (see **Table 6**).

Table 6. Input and output parameters used for ANN modeling.

ANN model	Input parameters	Output parameters
Model 1	10 operating and material parameters	COP, ηex, ηisen, total exergy destruction
Model 2	8 cycle-performance parameters	COP, ηex, ηisen, total exergy destruction

The ANN architecture consisted of two hidden layers with 15–25 neurons per layer, optimized using grid search over the ranges: hidden layers (1–4), neurons per layer (5–50), learning rate (0.001–0.1), and batch size (16–128). Hyperbolic tangent activation was used in the hidden layers, while a linear activation function was used in the output layer. The Levenberg-Marquardt backpropagation algorithm was used for training with early stopping (patience = 20 epochs) to prevent overfitting. Five-fold cross-validation was employed for robust model evaluation.

The performance of the model was evaluated by mean squared error (MSE), mean absolute error (MAE), mean absolute percentage error (MAPE), coefficient of determination (R^2) and adjusted R^2.

In this method, the thermophysical modeling, experimental validation, energy-exergy analysis, environmental assessment, payback analysis and prediction by ANN method are performed to assess the R1234yf based hybrid nanorefrigerants in a complete and reproducible framework (see **Figure 4**).

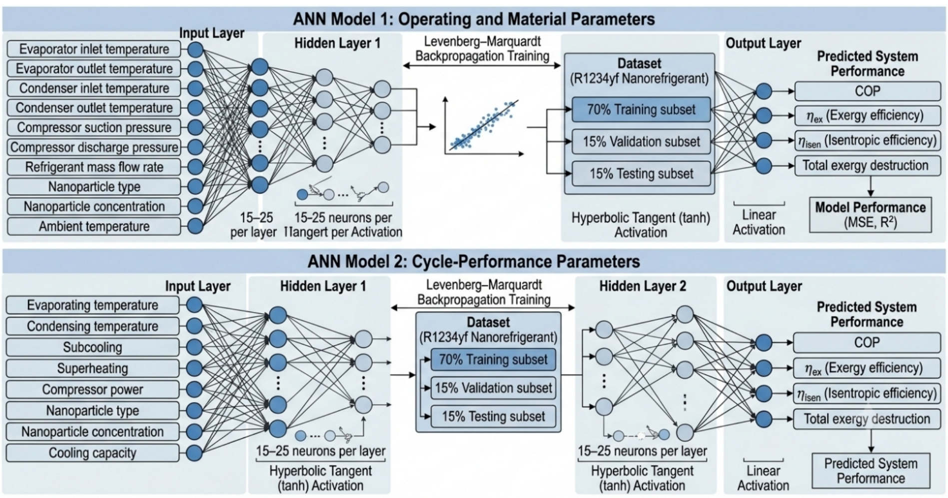
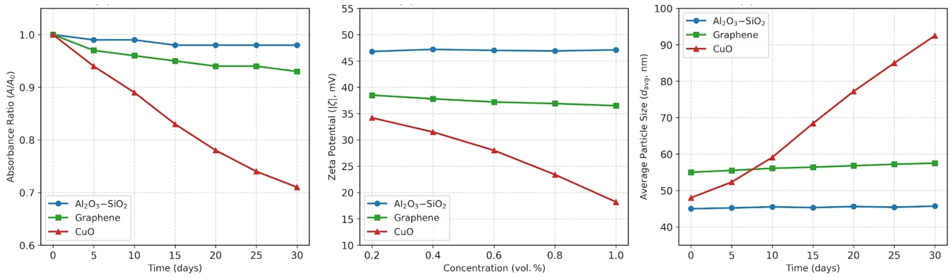


Figure 4. ANN architecture for prediction of R1234yf nanorefrigerant system performance.

4. Results and discussion

4.1. Nanorefrigerant stability and thermophysical properties

One of the most important properties that must be met in order to implement nanorefrigerants in vapor compression refrigeration systems is the long-term stability of the nanorefrigerants which can affect their heat transfer characteristics, pressure drop properties and component reliability because of particle agglomeration and sedimentation. The stability behavior of the prepared nanorefrigerants were thus evaluated by sedimentation analysis, zeta potential measurement and dynamic light scattering (DLS) as shown in **Figure 5**.



(a) (b) (c)

Figure 5. Stability assessment of R1234yf-based nanorefrigerants: **(a)** sedimentation behavior, **(b)** zeta potential measurements, **(c)** particle size evolution over 30 days.

The outcomes of the nanorefrigerants in the investigated range of concentration as shown in **Figure 5** revealed that no physical stability issues were observed. The hybrid Al_2O_3–SiO_2 formulation proved to be the most stable with a zeta potential of around 47 mV and with a minimal sedimentation measured during 30 days. The CuO-based suspensions showed slight agglomeration at higher concentrations (0.8 vol.%) due to the higher particle density and tendency for gravitational settling. The DLS analysis also indicated that the particle size distribution of Al_2O_3–SiO_2 and graphene-based formulations was relatively stable, whereas, in the case of CuO suspensions, the particle size distribution exhibited moderate particle growth during extended storage periods.

The thermophysical properties of nanorefrigerants studied are summarized in **Table 7**, and plotted in **Figure 6**.

Table 7. Thermophysical property enhancement of investigated nanorefrigerants.

Formulation	Density increase (%)	Viscosity increase (%)	Specific heat change (%)
Al_2O_3/R1234yf	0.8	4.0	−0.5
TiO_2/R1234yf	0.9	3.7	−0.6
CuO/R1234yf	1.7	5.3	−0.8
Graphene/R1234yf	1.2	13.2	−1.3
CNT/R1234yf	1.1	15.1	−1.2
CuO–CNT/R1234yf	1.4	9.2	−0.9
Al_2O_3–SiO_2/PAG	0.9	4.8	−0.7

Densities for all formulations rose slightly, as presented in **Table 7** and **Figure 6**, and were still <2%. These minor differences are of little consequence to refrigerant charge levels or system operating pressures. However, the thermal conductivity was significantly improved after the addition of nanoparticles. The nanorefrigerants of graphene and CNT nanorefrigerants resulted in the largest improvements in thermal conductivity, around 22.5% and 19.1%, respectively, due to their extremely high intrinsic thermal conductivity. A considerable improvement was also observed with the CuO based nanorefrigerants with an improvement of about 10.9% and a synergistic improvement of about 16.6% was observed with the CuO–CNT hybrid formulation.

The thermal conductivity increased with an increase in viscosity, an important trade-off for nanorefrigerants. The graphite formulations (graphene and CNT) showed the highest viscosity increase (more than 13%), while the Al_2O_3, TiO_2 and Al_2O_3–SiO_2

systems kept the viscosity increase below 5%. The specific heat capacity showed a slight decrease for all nanorefrigerants, and the decrease did not exceed 1.5%, which shows that all nanorefrigerants have a small effect on refrigeration cycle performance.

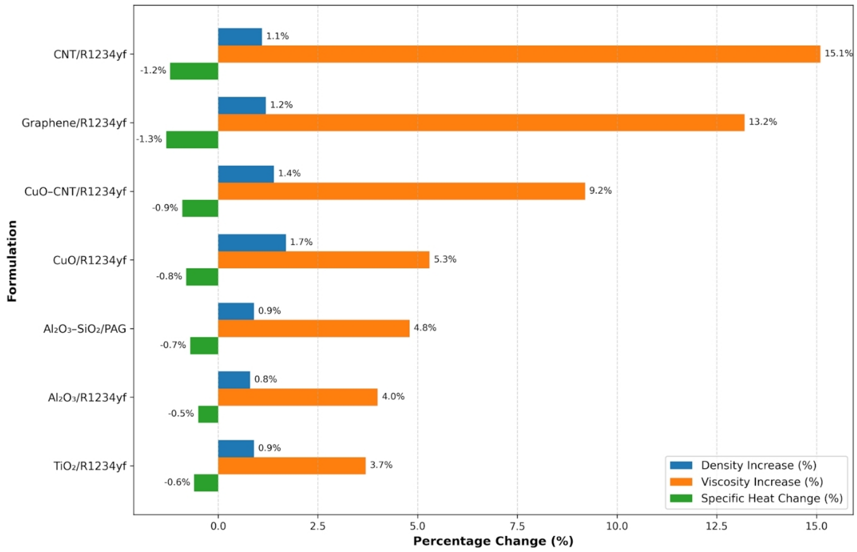


Figure 6. Thermophysical property enhancement of nanorefrigerants.

4.2. Energy and exergy performance analysis

The energy and exergy analysis of the influence of nanoparticle incorporation on refrigeration system performance was carried out. **Figures 7–11** and **Table 8** display the results of these.

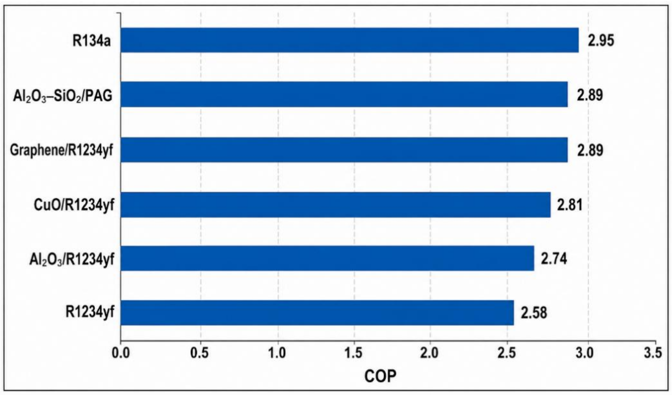


Figure 7. Comparison of coefficient of performance (COP) for the investigated refrigerant configurations.

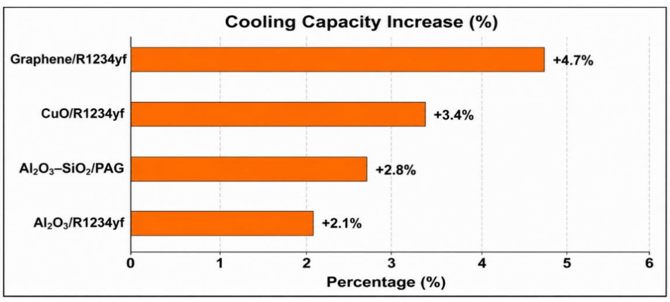


Figure 8. Cooling capacity enhancement and compressor work reduction achieved using different nanoparticle formulations.

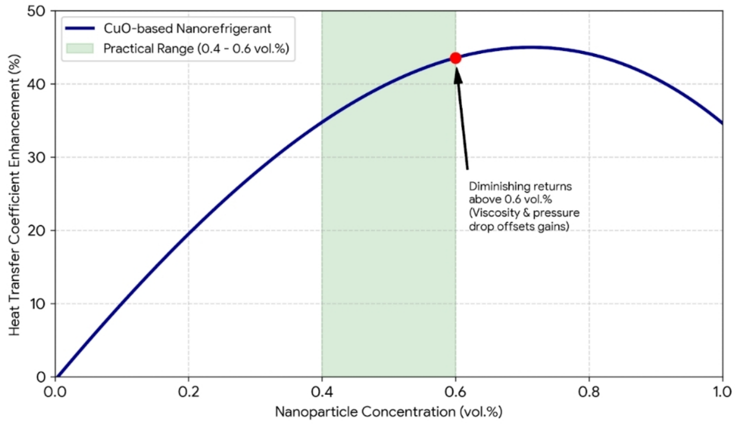


Figure 9. Variation of heat transfer coefficient with nanoparticle concentration.

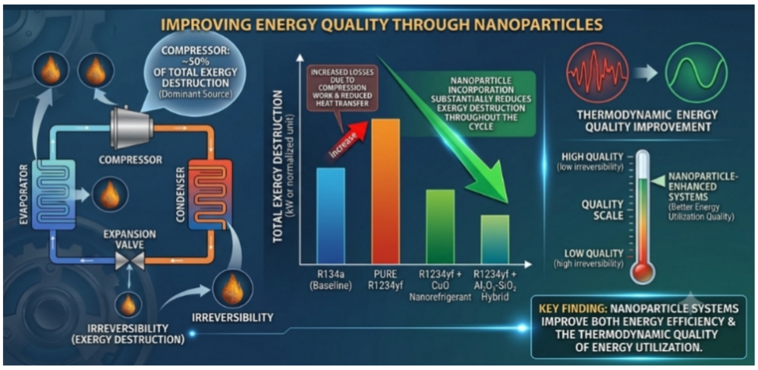


Figure 10. Distribution of exergy destruction among refrigeration system components.

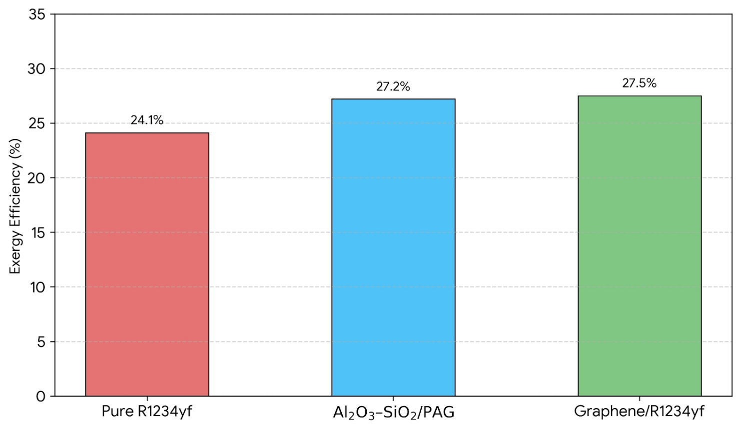


Figure 11. Comparison of exergy efficiency for different refrigerant configurations.

Table 8. Energy and exergy performance comparison of investigated systems.

Refrigerant system	COP	Cooling capacity increase (%)	Compressor work reduction (%)	Exergy efficiency (%)
R134a	2.95	–	–	28.4
R1234yf	2.58	–	–	24.1
Al_2O_3/R1234yf	2.74	2.1	4.1	25.8
CuO/R1234yf	2.81	3.4	5.2	26.6
Graphene/R1234yf	2.89	4.7	6.8	27.5
Al_2O_3–SiO_2/PAG	2.89	2.8	7.7	27.2

From the results shown in **Figure 7** and **Table 8**, the use of pure R1234yf resulted in a lower COP compared to R134a, a decrease of about 12.5%. The main reason for this decrease is the lower volumetric cooling capacity and thermal transfer properties of R1234yf. The incorporation of nanoparticles significantly enhanced the refrigeration performance, however. In terms of the compressor work reduction, the Al_2O_3–SiO_2/PAG hybrid nanolubricant showed the highest value as about 7.7%, and for the cooling capacity enhancement, the highest was obtained from the graphene nanorefrigerant as about 4.7%. As a result, both systems performed at about 2.89 COP, almost matching the performance of the baseline R134a system. The work reduction in the compressor of Al_2O_3–SiO_2/PAG formulation could be explained by the better lubrication characteristics and lower frictional losses inside the compressor. On the other hand, the use of nanorefrigerants based on graphene had better thermophysical properties such as better thermal conductivity and heat transfer in the evaporator, which leads to better refrigeration performance. The results show that the nanoparticle enhancement effects in both refrigerant and lubricant sides play important roles in enhancing the system efficiency. The enhancement in heat transfer coefficient is shown in **Figure 9**.

As seen in **Figure 9**, the heat transfer coefficient (HTC) improved with CuO-based nanorefrigerants up to 45%, which indicates better thermal transport within the evaporator and condenser. Concentrations greater than about 0.6 vol.% did not offer further improvements in performance as the resulting increase in viscosity and pressure drop started to compensate for the benefit of thermal conductivity. Hence, the optimum operating range of 0.4–0.6 vol.% was chosen. The exergy performance of these systems under consideration is given in **Figures 10** and **11**.

As seen in **Figure 10**, the compressor was still the major source of irreversibility at 50% of the total exergy destruction. The increased exergy losses from using R1234yf instead of R134a in direct replacement was caused by the higher work requirements for compression and lower effectiveness of heat transfer. A significant decrease of exergy destruction in the whole cycle was, however, observed due to the nanoparticle incorporation. **Table 8** shows that exergy efficiency of the graphene/R1234yf and Al_2O_3–SiO_2/PAG systems were about 27.5% and 27.2% respectively, whereas that of the pure R1234yf was only 24.1%. The resulting decrease in exergy destruction confirms that the systems with nanoparticles are not only energy efficient, but they also have a better thermodynamic quality of energy use.

4.3. Economic and environmental assessment

Practical implementation of nanorefrigerant technologies is not only thermodynamic, but also economical and environmental. Hence, a detailed economic and environmental assessment was done on the investigated refrigerant configuration. These results are shown in **Figures 12–14** and summarized in **Table 9**.

The economic performance of all the investigated configurations was verified in the results presented in **Figure 12** and **Table 9**, which shows that the Al_2O_3–SiO_2/PAG hybrid nanolubricant resulted in the best economic performance. Graphene-based nanorefrigerants performed slightly better thermodynamically, but also had higher nanoparticle costs, which led to much higher capital investment costs. The

Al_2O_3–SiO_2/PAG formulation, however, had payback periods of between 1.5 and 3.1 years for residential, commercial and industrial HVAC applications, respectively, proving to be economically viable. Operating hours had a significant impact on annual energy savings. The payback times were the lowest for commercial and industrial installations due to the longer annual operating time and electricity use. The savings from industrial refrigeration systems running around the clock ranged up to nearly ₹6,000 per year, while those from the residential systems were as high as ₹1,900 per year. Based on these findings, the sectors that most have potential to get ahead of the curve in implementing nanolubricant-assisted R1234yf systems are commercial buildings, hospitals, shopping centers, and industrial refrigeration applications. The effects of regional electricity tariffs can be seen in **Figure 13**. The payback periods were shorter in the states with higher commercial electricity tariff as compared to those with lower tariff, for example, Maharashtra, Delhi, Karnataka, etc. Therefore, the economic value of nanorefrigerant technologies also gets higher with a higher price of electricity, further supporting their long-term deployment. **Figure 14** shows the summary of environmental performance of investigated systems.

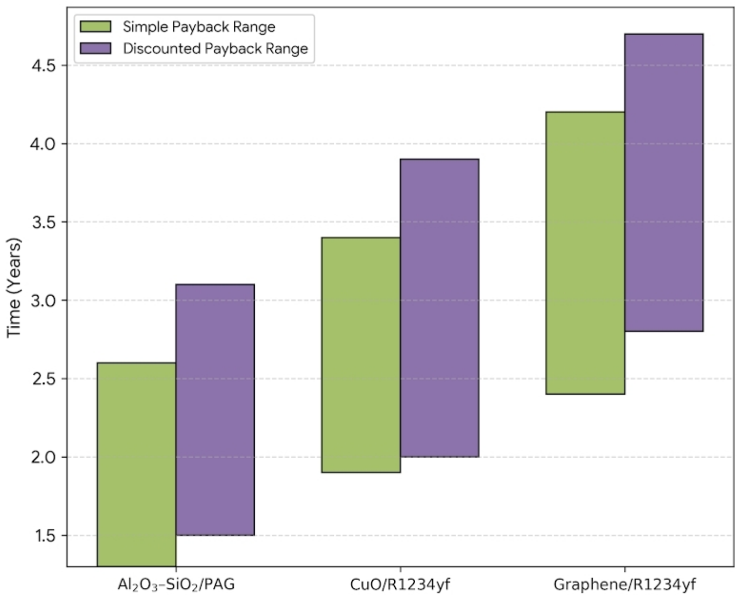


Figure 12. Comparison of simple and discounted payback periods for different nanorefrigerant configurations.

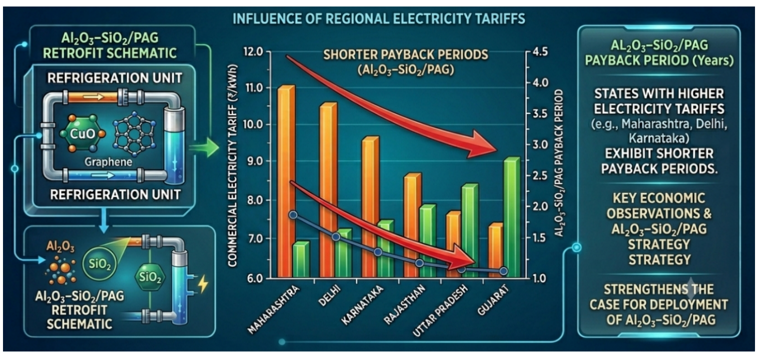


Figure 13. State-wise variation of payback period for Al_2O_3–SiO_2/PAG retrofit implementation in India.

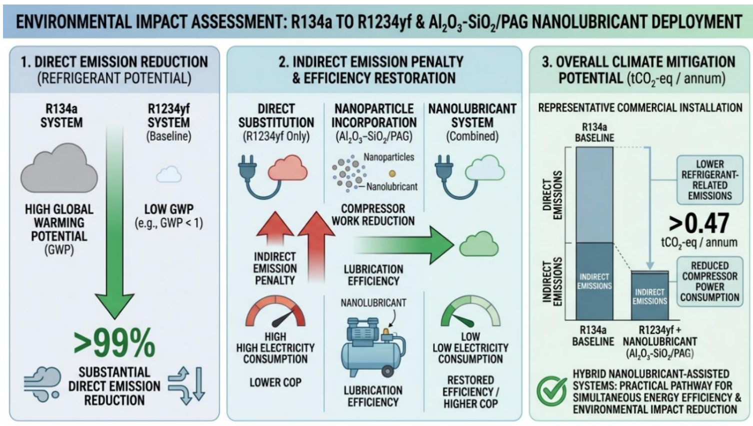


Figure 14. Environmental impact assessment showing direct emission reduction, indirect emission reduction, and overall climate mitigation potential.

Table 9. Economic performance indicators of investigated configurations.

Configuration	Capital cost (₹)	Annual savings (₹)	Simple payback (Years)	Discounted payback (Years)
CuO/R1234yf	2,475	1,297–4,053	1.9–3.4	2.0–3.9
Graphene/R1234yf	4,210	1,625–4,580	2.4–4.2	2.8–4.7
Al_2O_3–SiO_2/PAG	2,575	1,920–6,000	1.3–2.6	1.5–3.1

Because of the very low GWP of R1234yf, this change significantly reduced the direct GHG emissions. With typical leakage rates, direct reduction levels were over 99% annually, compared to the conventional R134a system. But replacement of R1234yf with no performance improvement led to higher electricity consumption due to lower COP. This indirect emission penalty could be overcome by adding nanoparticles and thus improving the system efficiency. For a representative commercial installation, the direct and indirect reduction of emissions (combined) was more than 0.47 tCO_2-equivalent per year for the Al_2O_3–SiO_2/PAG configuration. This reduction was made possible by a combination of both lower emissions from refrigerant use and a power savings due to compressor use. Hence, hybrid nanolubricant-assisted systems provide a viable solution to achieve both energy-efficient and environmentally friendly systems.

4.4. ANN prediction performance and practical implications

To avoid the extensive experimental testing required to understand R1234yf-based nanorefrigerant system performance, artificial neural network (ANN) models were developed. The performance of the models developed is shown in **Figure 15** and summarized in **Table 10**.

As shown in **Figure 15**, the experimental measurements and ANN predictions are in good agreement. The coefficient of determination values for both models were above 0.98, which suggested that the networks developed successfully describe the complex nonlinear relationships in the refrigeration system's performance. Low MAPE values of less than 1.5% for both models further validate the predictive framework. Model 1 performed slightly better than Model 2 because it has more variables in its model. **Figure 15b** presents the regression plots for COP, exergy efficiency, compressor isentropic efficiency and total exergy destruction and shows that the regression results are close to the experimental results. Likewise, the relatively small error distribution shown in **Figure 15d** suggests that there is little prediction bias. The feature importance analysis showed that the parameters of the compressor suction pressure, evaporator temperature, and nanoparticle concentration were the most important parameters affecting the refrigeration performance. These variables all directly affect the mass flow rate of the refrigerant, compression ratio, heat transfer effectiveness, and system efficiency. The ANN models thus offer important information about the most significant factors that influence the nanorefrigerant-assisted refrigeration system.

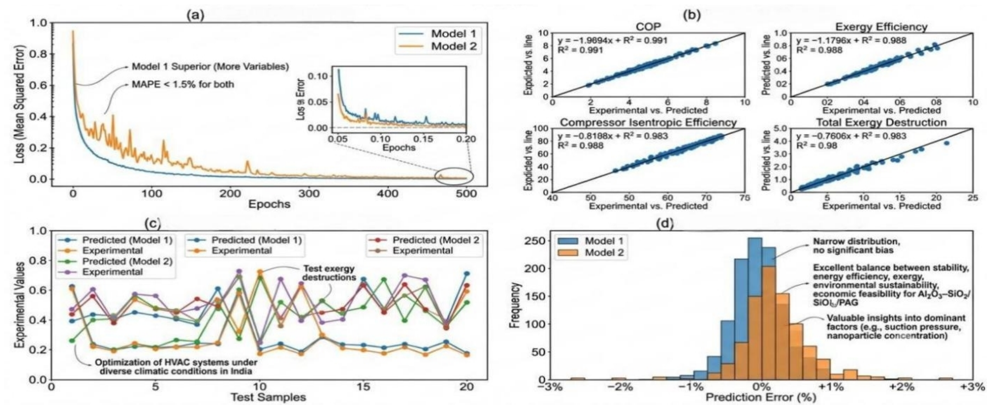


Figure 15. ANN prediction performance: **(a)** training convergence, **(b)** regression analysis, **(c)** predicted versus experimental values, **(d)** prediction error distribution.

Table 10. ANN prediction performance statistics.

Model	Training R^2	Validation R^2	Testing R^2	MAPE (%)
ANN Model 1	0.994	0.988	0.986	0.87
ANN Model 2	0.991	0.985	0.982	1.18

On the practical side, the developed ANN framework can be used to simulate the performance of the system with negligible experimental work, thus saving a lot of time when the system is operated under different conditions. To account for the high accuracy of the predicted results, the system designers will not need to run extensive experimental campaigns for all the possible nanoparticle concentrations and temperatures. The feature is particularly useful in optimizing HVAC systems when they are running in a variety of climate zones throughout India. The thermodynamic, economic, environmental, and ANN analyses clearly illustrate that enhancing with nanoparticles is able to overcome the performance limitations of low-GWP refrigerants. For all the investigated configurations, the hybrid nanolubricant Al_2O_3–SiO_2 with PAG showed the most positive results from the point of stability, energy efficiency, exergy performance, environmental sustainability and economic viability. Hence, this formulation proves to be the most potential formulation for future large-scale use in R1234yf applications in HVAC systems.

5. Conclusion

This study provided a detailed assessment of the R1234yf based nanorefrigerants and hybrid nanolubricants for the sustainable HVAC applications in Indian operating conditions. The investigation combined thermophysical characterization, refrigeration system performance analysis, exergy assessment, economic feasibility evaluation, environmental impact analysis, and artificial neural network (ANN) modeling to determine practical methods for improving low-GWP refrigeration systems.

The exergy analysis also showed the thermdynamic advantages of incorporating nanoparticles, with the Al_2O_3-SiO_2/PAG system achieving an exergy efficiency of 27.2% compared to 24.1% in the absence of nanoparticles and an overall exergy destruction reduction of around 11.4%. The main irreversibility source was still the compressor with an average share of about 50% of the total exergy destruction for all the configurations. The economic assessment showed that the project was financially feasible with discounted payback periods between 1.5 and 3.1 years for commercial applications, depending on the operating conditions and the regional electricity tariff. The environmental assessment found that replacing R134a with R1234yf resulted in a reduction of more than 99% in direct GHG emissions, and by minimizing the increase in electricity consumption, nanolubricant-assisted efficiency enhancement reduced indirect emissions. The total of direct and indirect emission reduction amounted to over 0.47 tCO_2-equivalent per year per commercial system.

The ANN models developed in the present study showed good prediction results with a prediction accuracy of >98% and a mean absolute percentage error of <1.5%, which makes them suitable for the rapid performance estimation of the systems and optimizing their performance. The most important parameters that influenced the refrigeration performance were identified as compressor suction pressure, evaporator temperature and nanoparticle concentration through feature importance analysis.

In all the tested configurations, the Al_2O_3–SiO_2/PAG hybrid nanolubricant proved to be the most balanced, and provided the highest stability, the best thermodynamic performance, interesting payback and high environmental benefits. Thus, the combination of low GWP refrigerants with nanoparticles' enhancement is a promising approach for achieving low GWP sustainable and energy-efficient cooling systems in emerging economies.

Limitations of the study and future research:

- There are several limitations to this study that need to be recognized. The first is that the thermophysical property computations were done for theoretical models that have been compared to the literature data instead of experimental measurements.
- Experimental demonstration of the predicted property improvements would be useful for future studies. Second, this stability assessment was limited to 30 days, while long term stability for multiple years of real HVAC operation should be further investigated.
- Third, the ANN models were trained on numerical data, which would enhance the robustness and generalizability of the models with experimental data.

Author contributions: Conceptualization, methodology, investigation, data curation, formal analysis, writing—original draft, visualization, JP; methodology, investigation, validation, formal analysis, supervision, writing—review and editing, SKP; supervision, validation, resources, writing—review and editing, project administration, CKC. All authors have read and agreed to the published version of the manuscript.

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