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Review Article

Review of Alternative Refrigerants R32 and R1234yf with Nanofluid Applications for Enhanced Performance of Air Conditioning Systems

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Abstract - *The Refrigeration and Air Conditioning (RAC) sector is undergoing a major shift in gears in accordance with the international environmental regulations that mandate a reduced rate of emission of greenhouse gases. Traditional fridges like R134a and R410A are highly efficient, but have a high Global Warming Potential (GWP), which makes them not viable in the long term. There has appeared an opportunity for low-GWP alternatives, especially R32 and R1234yf, with desirable thermophysical characteristics and lesser environmental effects. In order to improve the performance of the system and increasing heat transfer, the use of nanoparticles has been increased. In this review article, the research articles based on the application of nanofluids using R32 or R1234yf in the vapor compression systems has been critically reviewed. The focus is on the increase of the Coefficient of Performance (COP), exergy efficiency, reduction of compressor work, and the temperature of discharge. The possible applications of such combinations to achieve a high level of energy savings and sustainability goals are demonstrated by comparative analysis with the base refrigerants. However, some issues, such as stability of nanoparticles, compatibility with materials, flammability, and the scalability of cost, continue to be major obstacles to generalization. Future research directions, such as advanced hybrid nanofluids, predictive modeling with AI/ML assistance, life cycle and techno-economic analysis, and the formation of an international standard, are also found in the article. All in all, creating a novel approach to nanofluids that incorporates refrigerants like R32 and R1234yf is a promising avenue in the development of the next-generation, high-efficiency, and environmental friendly air conditioning systems.*

Keywords - *Low-GWP refrigerants, R32, R1234yf, Nanofluids, Air conditioning systems.*

1. Introduction

The issue of climate change and global warming has placed significant pressure on the RAC sector to minimize its environmental footprint. Conventional refrigerants such as R134a and R410A, though widely used for several decades, have been identified as major contributors to global warming due to their high Global Warming Potential (GWP). Such high-GWP refrigerants have been gradually but surely phased out and substituted with alternative substances using international agreements, notably, the Montreal Protocol, and its follow-up Kigali Amendment which have outlined the efforts to reduce the harm to the environment and establish a sustainable cooling industry [1].

R32 and R1234yf are two of the promising alternatives with relatively low GWP and zero Ozone Depletion Potential (ODP). The ideal properties of environment friendly refrigerant are illustrated in Figure 1. R32 has been reported to be energy efficient with good thermodynamic properties, but mild flammability poses some difficulties in its handling. R1234yf, a hydrofluoro-olefin (HFO) family, on the other hand, is associated with an ultra-low GDP, which is what makes it especially applicable in the long-term adherence to the environmental regulations. It is with increased adoption in both mobile and stationary air conditioning systems as substitutes to traditional HFCs that both refrigerants are being increasingly adopted [2].

In addition to R-32 and R-12345yf, several other non-GWP refrigerants have also been investigated as potential alternatives to conventional HFCs. Currently, attention has been drawn to natural refrigerants—such as propane (R290) and carbon dioxide (R744) —due to their extremely low environmental impact, as well as their favorable thermal and physical properties. However, before utilizing this refrigerant, there is always one crucial consideration: its practical implementation is limited due to safety concerns and design constraints. The R290 is classified under highly flammable refrigerant, therefore it is important to use the refrigerant with caution. As the CO_2 based refrigeration system works at very high pressure, so it is very important to design the components very carefully. It is important to consider the environmental impact, the compatibility of the refrigerant with the existing system, while considering the various alternatives like R-1234y and R32. It was observed that when the nanofluid is mixed with the base fluids, the resultant nanofluid shows better energy usage, heat transfer behaviour, and thermal Conductivity. When the nano particles dispersed in the base fluid, the resultant nanofluids emerged as a sustainable solution [3, 4].

However, it was observed in literature that all the researchers have performed their studies by using the nanofluid individually and studied its heat transfer capability. Very few researchers have used the R-32 and R-1234yf refrigerants in combination.

The researchers have not developed a complete strategy wherein the complete development, right from system design, strategy of instruments, and data procedure is mentioned.

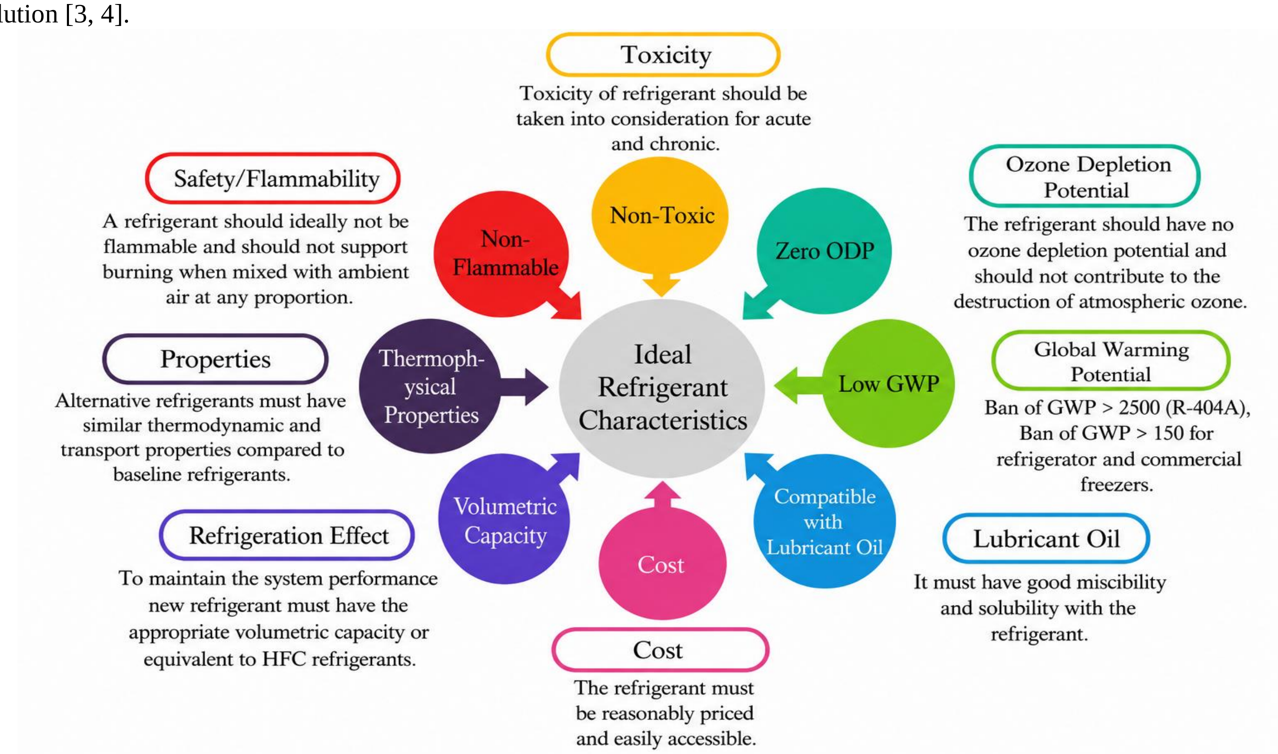

Fig. 1 Ideal characteristics of environment friendly refrigerant [5]

The aim of this review article is to present a complete review wherein the development of R32 and R1234yf use in the air conditioning system is thoroughly studied. In this article, the environmental impact, operating performance and thermal characteristics associated with the applications of nanofluid are presented along with the problems associated with it.

Hence, it can be pointed out that the novelty of this review article not only lies in the usage of refrigerant with nanofluid, but also it mentioned the use of the system. This study contributes in providing a pathway for the energy efficient system that is sustainable and environment friendly.

2. Overview of Alternative Refrigerants in Air Conditioning

In this review article, only those publications are selected which are relevant to low GWP refrigerants and are used with the naofluids in VCR systems. The well-known and genuine resources such as Science direct, web of Science, and google scholar database have been searched to identify the relevant journal papers and proceedings of conference. The keywords and their combinations, like R32 refrigerant, R1234yf, low-GWP refrigerants, refrigerant heat transfer, and vapor compression systems has been utilized. While carrying out the literature review, the articles from 2010 to 2025 has been studied thoroughly and properly synthesized. Whenever required, the old research articles has also been identified to consider their research contributions.

2.1. R32

R32 is a hydrofluorocarbon (HFC), which has established much attention as an auxiliary for R410A in air conditioning. It has a zero ODP and a GWP of approximately 675, which is almost 3 times less than that of R410A. Its thermophysical characteristics are boiling point of -51.7^{0}C, critical temperature of approximately 78.1^{0}C, therefore, making it useful as a part of the refrigeration vapor compression cycle, with similar performance to traditional refrigerants [6].

Operationally, R32 has better COP and volumetric cooling capacity than R410A. It also has lower requirements of mass flow and can enable less compressor displacement, and can make systems less expensive. The higher discharge temperature is, however, one of the limitations as it may influence the reliability of the compressor unless it is properly controlled by making amendments to the designs by introducing liquid injection or enhanced cooling mechanisms. Another relevant factor is safety: R32 has the classification of A2L, i.e. flammable (rather mildly), yet not very toxic. It can therefore only be extensively used with the proper system design and safety standards [7, 8].

2.2. R1234yf

R1234yf is a hydro-fluoro-olefin (HFO) specifically developed to replace R134a in mobile and stationary air conditioning systems. It has been extensively acknowledged as an environmentally benign refrigerant which is currently available with an ultra-low GWP of less than 1 and zero ODP. Its boiling point is -29.5°C, and the critical temperature is about 94.7°C, which makes it thermodynamically compatible with systems originally designed for R134a, albeit with some modifications [9].

In terms of market adoption, R1234yf has already become the industry standard in automotive air conditioning in Europe, North America, and several parts of Asia due to regulatory requirements. Stationary applications are also gradually expanding, especially in split-type air conditioners and heat pumps. The major advantage of R1234yf lies in its extremely low environmental impact, which ensures long-term compliance with international climate agreements [4, 10].

Nevertheless, R1234yf presents challenges related to flammability, as it is also classified as an A2L refrigerant. Even though the velocity of spread of fire is not that high, precautions should be taken when designing and installing the system, as well as when servicing. Moreover, its thermophysical characteristics are slightly different as compared with R134a and, thus, the energy efficiency is somewhat lower unless the optimization of the systems is taken. With these restrictions, its use is still on the rise due to its regulatory as well as environmental gains [11].

2.3. Comparative Analysis of R32, R1234yf, and Conventional Refrigerants

The replacement of traditional refrigerants (R134a and R410A) with others (e.g. R32 and R1234yf) is not merely mandatory because of contamination regulations, but also due to performance and environmental benefits that substitutes present. R32 is more efficient and offers greater cooling capacities, and R1234yf does have unmatched decreases in GWP [12].

Table 1 presents a summary of thermophysical and environmental characteristics of such refrigerants.

Table 1. Comparative properties of conventional and alternative refrigerants [12]

Refrigerant	Chemical Type	Boiling Point (°C)	Critical Temp (°C)	GWP	Safety Class	Key Features
R134a	HFC	–26.1	101.1	~1430	A1 (non-flammable, low toxicity)	Widely used; high GWP
R410A	HFC blend	–51.6	72.5	~2088	A1 (non-flammable, low toxicity)	High pressure, high GWP
R32	HFC	–51.7	78.1	~675	A2L (mildly flammable, low toxicity)	High efficiency, higher discharge temp
R1234yf	HFO	–29.5	94.7	<1	A2L (mildly flammable, low toxicity)	Ultra-low GWP, slightly lower COP

The analysis of the research article shows that the single refrigerant is not capable because of its inherent drawbacks, whereas the combination of R32 and R1234yf provides a balanced approach in between efficiency and sustainability.

3. Nanofluids In Refrigeration Systems

The constantly increasing demands to improve the energy efficiency of the refrigeration and air conditioning subsystems lead scientists to think of employing innovative and improved working fluids, better in terms of thermal properties. The conventional refrigerants are efficient, although they are normally restricted with regard to heat transfer, which limits the work of the system [13, 14]. To solve these issues, nanofluids, fluids that are compatible by incorporating nanoscale particles into an underlying fluid, refrigerants or lubricants, have emerged as a solution. Combining the quality heat transfer properties of nanoparticles, nanofluids could tremendously improve the overall performance type of heat transfer, reduce energy consumption, and enhance the overall COP of vapor compression systems [15].

3.1. Types of Nanofluids

Given refrigeration systems, some significant groups of nanofluids can be based on the type of nanoparticles used in the base. The most commonly studied of nanofluids are metal oxide nanofluids. They are popular because their synthesis processes are quite simple, they have good chemical stability, and they are inexpensive. Common examples include aluminum oxide (Al2O3), titanium dioxide (TiO2), Zinc oxide (ZnO) and copper oxide (CuO). The experimental research has unendingly indicated that these metal oxide nanofluids are able to augment the significance of the thermophysical properties, including thermal Conductivity and the heat transfer coefficients that are directly associated with the performance enhancement of vapor compression refrigeration, air conditioning units [16].

Another possible material of value is the carbon-based nanofluids that consist of Carbon Nanotubes (CNTs), graphene, and graphene oxide nanoparticles. The materials are also very attractive as they may have very high intrinsic thermal Conductivity that can substantially increase the overall heat transfer of the working fluid. However, practical issues, such as the achievement of a homogeneous dispersion, long-term consistency, and controlling the rise of the viscosity, are also problematic. Care must be taken to address these issues in a bid to optimise the benefits of carbon-based nanofluids in the highly efficient refrigeration systems in practice [17].

In recent years, hybrid nanofluids have emerged as a promising approach to combine the advantages of different nanoparticle types. Adding two or more nanoparticles, including Al2O3 with CNTs or CuO with graphene, researchers hope to capitalize upon synergies that both improve thermal Conductivity and offer increased suspension stability [18, 19].

With hybrid formulations, it is possible to more closely adjust thermophysical properties, without compromising between heat transfer enhancement and controllable viscosity and flow behaviour. Consequently, hybrid nanofluids have been contemplated as high-performance and next-generation refrigeration and air conditioning systems, with efficiency and reliability being the most crucial factors [6, 11].

3.2. Thermophysical Enhancements of Nanofluids

Introduction of nanoparticles into the base fluids greatly alters their thermophysical characteristics that consequently affect the overall functioning of refrigeration systems. Among the most evident effects is the effect on the thermal Conductivity. Since nanoparticles have high intrinsic thermal Conductivity, they can improve the effective heat transfer of the fluid. This enhancement will enable more effective energy transfer between the refrigerant and heat exchanger surfaces, such as evaporators and condensers. It has been documented through experimental research that metal oxide-based nanofluids such as Al2O3, CuO, and TiO2 can provide thermal conductivity increases of up to about 10-40%, depending on the nature of the nanoparticle, its concentration, and the particle size distribution. This type of improvement can be especially useful in small or highly loaded air conditioning systems, where heat transfer usually is the constraint [12].

Table 2. Comparative thermophysical properties of selected refrigerants [12]

Property	Unit	R134a	R410A	R32	R1234yf
Boiling Point	°C	–26.3	–51.6 (mixture)	–51.7	–29.5
Critical Temperature	°C	101.1	72.5 (mixture)	78.1	94.7
Critical Pressure	MPa	4.06	4.83	5.78	3.39
GWP (100-year horizon)	–	1430	2088	675	4
Ozone Depletion Potential (ODP)	–	0	0	0	0
Latent Heat of Vaporization	kJ/kg	216	210	218	218
Density (liquid, 25°C)	kg/m³	1207	1040	1207	1220
Specific Heat Capacity (liquid, 25°C)	kJ/kg·K	1.43	1.21	1.5	1.42
Thermal Conductivity (liquid, 25°C)	W/m·K	0.081	0.079	0.082	0.081

While higher thermal Conductivity contributes positively to system efficiency, the addition of nanoparticles also impacts the viscosity of the fluid. Higher viscosity may raise the amount of power needed to pump the refrigerant and may offset some of the energy savings gained from improved heat transfer. Consequently, careful selection of nanoparticle concentration is essential. According to optimization studies, too heavy loading of nanoparticles can result in diminishing returns since the effect on the net performance benefit is to become negative as the flow resistance increases. In a bid to achieve the total system energy efficiency, such effects need to be balanced to avoid them creating an additional mechanical stress on the system parts [20].

The other property that is influenced by the nanoparticles is the specific heat capacity of the fluid. The reduction in particular heat has been observed to occur as a result of increasing the concentration of nanoparticles in a few studies. Such behaviour can undermine the thermal behaviour of the system, especially when the system is applied in an energy storage process or when the system is not operated steadily. A refrigerant containing a smaller specific heat can pick up or lose relatively less or relatively more energy per unit mass, and this should be taken into consideration in system design and sizing to ensure that thermal control is adequate [21].

Among the most practical challenges of using nanofluids in a practical setting is the fact that it has to be stable within a sufficiently longer duration of operation. When nanoparticles are used, they are prone to peptidization or settle particularly in low-viscosity refrigerants or when subjected to hot conditions. Such aggregation reduces the thermal effectiveness and can lead to the pumps, compressors, and small passages of heat exchangers being contaminated, obstructed, or eroded. In order to overcome these challenges, different authors have used various methods such as ultrasonication (Figure 2), surfactants, and surface functionalization of nanoparticles. These mentioned methods are useful to increase the stability of dispersion, enhance stability and guaranteed constant thermal behaviour over a long period of time. So it is very important to stabilize the suspension of nanofluid, and the efficiency of nanofluid is very much dependent on this factor [15].

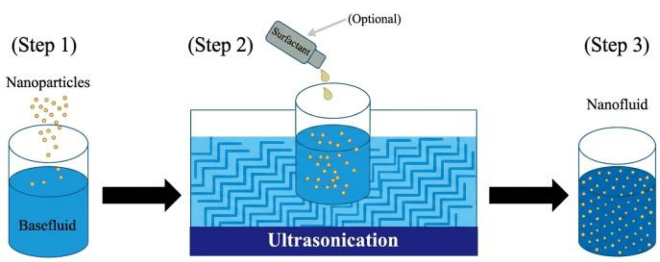

Fig. 2 Ultra sonication [15]

3.3. Heat Transfer Mechanisms with Nanoparticles in Refrigerants and Lubricants

Both the factors, micro and macro effects, increases the thermal efficiency by increasing the heat transfer of the nanofluid-based systems. One of the factors who is contributing more in enhancing the heat transfer is the Brownian motion of nanoparticles. The random, thermally induced movement of these particles generates localized micro-convection within the fluid. This is because microscopic agitation augments energy exchange at the particle-fluid interface and eases the smoother transportation of thermal energy to and cooling of temperature changes in the system [22].

The other significant process is the establishment of liquid layers at the solid-liquid interface. Dispersed nanoparticles in the underneath fluid are likely to generate a highly organized structure of molecules within the layer that is immediately over the underlying fluid. This structured hetero-surface interface layer possesses a high thermal conductivity when compared to the underlying fluid, and is a high thermal conductivity conduit or pathway. Thin channels and heat exchanger surfaces are also found in this layer, particularly, and the more the microscale conduction, the higher the performance of the entire system can be [23].

At a certain concentration of the particles, nanoparticle clustering and percolation networks could be produced. The continuous exhibits or chain-like structures create continuous conductive pathways in the fluid that are very efficient in reducing thermal resistance. These clusters increase the overall thermal Conductivity of the nanofluid because they provide the nanofluid with favorable heat-conducting pathways. Particle concentration must be carefully maintained, though, since too much can cause a problem of sedimentation or resist flow [24].

Enhanced boiling heat transfer is achievable in refrigerant-based nanofluids because of the interaction between nanoparticles and hot surfaces. As nanoparticles are deposited on the walls of evaporators or boilers, their deposition modifies the surface roughness, changes the density of nucleation sites and changes the wettability. The modifications also enable the efficient formation and detachment of the bubble in both pool boiling and flow boiling process which leads to high heat transfer rates. Such surface changes are only relevant in the stability of temperature gradients and thermal overcoming resistance in phase change processes [25].

Nanoparticles can also be enriched by compressor lubricants, other than being affected by thermal effects. With the combination of lubricants, they reduce the friction and wear, decreasing the impact and thus improving the mechanical efficiency and the extended component life. Secondly, nanoparticles can also be used to enhance the solubility of oil and refrigerant in evaporators and condensers to improve heat transfer. It is one of the peculiarities of nanofluid-lubricants that can be particularly attractive to advance the further development of the sphere of air conditioning and refrigerated papers: these systems represent two-sided improvements with thermal and mechanical characteristics [26].

Overall, with the inclusion of nanoparticles in refrigerants and in lubricants, there will be a massive potential in improving the heat transfer and performance. Nevertheless, in order to achieve superior results, it is vital to pay particular attention to the concentration of particles, the ways of stabilization, and compatibility with the parts of the systems. The use of nanofluids will thus require sound designing and engineering techniques in order to maximize the advantages it potentially holds in the real world application, as far as refrigeration systems are concerned [27].

4. Application of Nanofluids Containing R32 and R1234yf

Even though R32 and R1234yf were reported as one of the promising next-generation refrigerants, thermophysical constraints of these compounds can continue to limit their use in conventional systems, such as poor heat transfer properties and elevated temperature discharges by the compressor. In order to solve these issues, scholars have conducted a study on the use of nanofluids in refrigeration systems. Introduction of nanoparticles in refrigerants or lubricants makes it possible to increase the thermal Conductivity and the heat transfer coefficient, as well as the lubrication characteristics in mass production, thus contributing to higher efficiency in the system and reduced energy consumed. This section provides a brief discussion of the findings of experimental findings and numerical studies that have demonstrated the potential of nanofluids when applied to vapor compression systems containing R32 and R1234yf.

4.1. Experimental Studies on R32 with Nanofluids

Few authors have attempted to evaluate the performance of mixing the nanoparticles into R32 based system. The authors have either directly introduced the nanoparticles in the refrigerant or indirectly through compressor lubricant [16, 17]. The addition of nanoparticles such as Al_2O_3, TiO_2, CuO, and graphene derivatives has been shown to enhance the heat transfer coefficient in both evaporators and condensers. This improvement is primarily due to increased thermal Conductivity and modified surface boiling characteristics.

One of the results that is evident in experiments is the increase in COP. As a case example, it was demonstrated that systems containing R32 and Al_2O_3 nanofluid increased COP by 8-15% relative to pure R32. This boost in COP can be associated with the decreased compressor workload along with the enhanced heat transfer, because the enhanced lubricant-refrigerant miscibility reduces the frictional loss. [20]. Figure 3 indicates the COP of refrigerant compressors (a) R32 and (b) R134a.

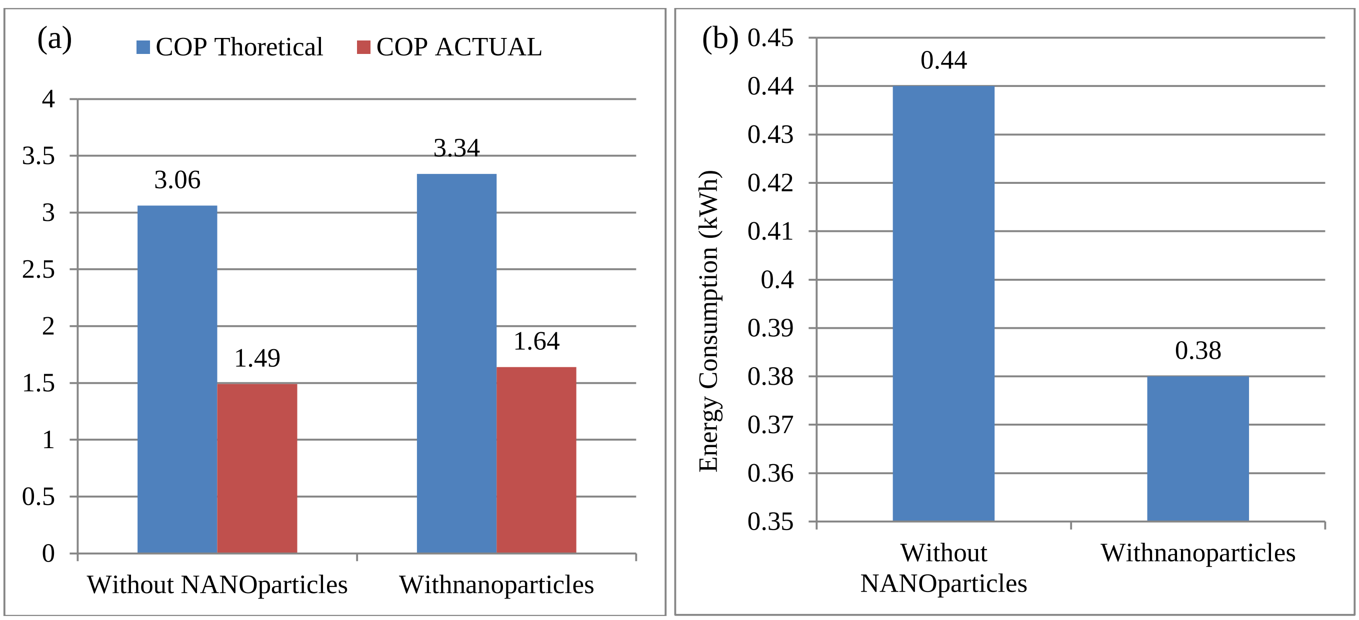

Fig. 3 COP for refrigerant compressors (a) R32 and (b) R134a [21]

The other observation that has been constant is the energy saving and compressor work reduction. Nanofluids can reduce the operating temperature of compressors by enhancing the lubrication and heat dissipation properties of the fluids, thereby increasing the life of the component and decreasing power consumption. The areas where the heat rejection is critical, in such situations the optimised structures have shown energy savings of up to 10%. But there is always a big challenge associated with the stability of nanoparticles in R32 systems. In order to tackle these challenges, advanced preparation methods such as surfactant-assisted dispersion or hybrid nanoparticles are being continuously explored.

4.2. Experimental Studies on R1234yf with Nanofluids

Research on nanofluid applications with R1234yf is comparatively more recent but has gained momentum with the rapid adoption of this refrigerant in automotive and domestic air conditioning. Studies have demonstrated that dispersing nanoparticles into R1234yf or its associated lubricants leads to significant performance improvements compared with conventional oil-based systems.

R1234yf mixed with nanoparticles like TiO2 and CNTs has demonstrated better cooling efficiency in the transient loading situation in automotive air conditioning. It has been demonstrated that it has lowered outlet temperatures in evaporators and minimized pull-down times, which is desirable in vehicle cooling. In addition, nanoparticle lubricants can also reduce the compressor driving powers and hence less fuel is used and consequently indirect reduction of CO2 emission.

Domestic or stationary systems containing R1234yf with nanofluids have also been demonstrated to exhibit a large increase in COP at 5-12. The major aspect that has been discovered in this enhancement is the increase in the heat transfer in evaporators and condensers. It is worth noting that the nanofluids can also be used to minimize the efficiency penalty observed respectively in pure systems of R1234yf compared to R134a.

4.3. Simulation and Numerical Investigations

In addition to experimental studies, studies with simulation and numerical methodologies to test the efficiency of nanofluid-refrigerant mixtures are also on the upswing, even though they are more. These would help to extrapolate system behavior under varied operating conditions and even maximize behavior without incurring the high expense as would be incurred by conducting an enormous amount of tests.

Using CFD models, the simulating of the nature of heat transfer by evaporators and condensers charged with nanofluid-charged R32 and R1234yf systems has been performed. Some of the common effects that are modeled include particle concentration, flow regimes and modification of the surface of the heat transfer coefficients of nanopaceted particles. Boiling heat and convective transfer are continuously improving in experiments as compared to the base refrigerant.

Thermodynamic modeling has also been widely used to predict cycle performance indicators (COP, exergy efficiency and compressor work). These models also contribute towards the comprehension of the optimum concentrations and operating concentrations of the nanoparticles, as the nanofluid property correlations are incorporated in the models.

Table 3. Comparative summary of studies on R32 and R1234yf with nanofluids

Study	Refrigerant	Nanoparticle	Method	Concentration	Major Findings
[28]	R600a	TiO_2	Experimental	0.5 g/L	Reduced energy consumption by **9.6%** and improved refrigerator performance.
[29]	LPG	TiO_2, SiO_2, Al_2O_3	Experimental	Low concentration (not specified)	TiO_2 and SiO_2 reduced power consumption by **13%** and **12%**, respectively.
[30]	R134a	Al_2O_3	Experimental	0–15 vol.%	Maximum **COP of 6.5** achieved using 15 vol.% Al_2O_3 nanofluid.
[31]	R134a, R1234yf	Cu, Al_2O_3, CuO	Numerical	0–5 wt.%	COP improved by **5–6%**; heat transfer increased by **6%**.
[32]	R1234yf	TiO_2, Al_2O_3	Experimental	0.5 mass%	TiO_2 improved cooling capacity by **12%** and reduced power consumption by **28.1%**.

5. Modelling of Solar Dryers and PCM

The efficiency of the vapor compression-generated AC systems and environmental policies has become an urgent subject on the research agenda among scholars as they seek to guarantee the efficacy of the alternative refreshment and nanofluid-enhanced mixtures of refrigerant. The traditional baseline coolants like R134a and R410A have been used extensively in commercial and residential applications, but due to their large Global Warming Potential (GWP) and environmental factors, the search to find alternatives that are eco-friendly has been conducted.

Unlike the previously discussed HFCs that have a high GWP, low GDP, and satisfactory thermophysical characteristics, HFOs such as R1234yf, as well as HFCs such as R32, have come to the forefront as promising alternatives because of their low GDP, improved thermophysical properties, and safe operating margins. Moreover, it has been found that the dispersion of nanoparticles (e.g. Al2O3, CuO, SiO2, TiO2 and those based on graphene) in refrigerants can also be exploited to further improve the performance of systems by increasing the efficiency of heat transfer, reducing compressor work and cutting the irreversibility losses.

In several experimental and numerical works, a comparative analysis of baseline refrigerants and R32, R1234yf, and blends of R32 with its nanofluids has been conducted. The indicators of performance that are usually looked at are the COP, the exergy efficiency, the discharge temperature of the compressor, the pressure ratio and the total energy that can be saved.

Through published literature, they have noted that refrigerants, whose nanoparticles have been blended, tend to have a significant 5-15% higher COP than their conventional refrigerant counterparts. As an example, the substitution of R134a with R1234yf in combination with the Al_2O_3 nanoparticles not only decreased the discharge temperature of the compressor but also improved the heat transfer in the evaporation system, the exergy efficiency tended to be higher. In the same way, R32 and CuO nanofluids showed decreased entropy production and enhanced second-law efficacy in split-type air conditioners.

In terms of sustainability, R32 and R1234yf fall dramatically below the GWP values of traditional refrigerants; hence, they are reasonable options, whereas others are not. Introduction of nanoparticles has been found to slightly lower the energy usage in long-duration AC operation, and this could result in significant savings on a large scale. The comparative performance evaluations are summarized in Table 3, focusing on both experimental and simulation-based outcomes.

Table 4. Comparative performance of baseline refrigerants vs. R32/R1234yf with nanofluids

Study	Refrigerant	Nanoparticle	Application	Method	Concentration	Major Findings	Research Gap
[33]	R134a	Al_2O_3	Nanolubricant	Experimental	Not specified	25% lower power consumption.	Low-GWP refrigerants not studied.
[34]	VCRS	Al_2O_3	Nanofluid	Experimental	0.001–0.01 wt.%	COP improved by 25.7%.	Long-term performance not evaluated.
[35]	R134a	SiO_2, CuO	Nanorefrigerant	Experimental	Not specified	CuO enhanced heat transfer significantly.	Only boiling heat transfer is studied.
[36]	R134a	CuO	Nanolubricant	Experimental	0.5–2 wt.%	Boiling heat transfer increased.	System performance not investigated.
[37]	R134a	SWCNH, TiO_2	Nanolubricant	Experimental	Not specified	Improved lubricant properties.	Cooling performance not reported.
[38]	R134a	CuO (10 nm)	Nanolubricant	Experimental	0.025–0.30 wt.%	COP improved by 35.89%.	Only CuO nanoparticle investigated.

6. Challenges and Limitations

Even though the usage of low-GWP refrigerants, comprising R32 and R1234yf, with nanofluids, displays noteworthy energy efficiency and sustainability improvement, amount of trials and constraints essential to be dazed already the technologies can be practical to marketable and housing air conditioning schemes.

A change to the laboratory-level demos to the real-life use must be sensibly reflected in standings of practical, protection, and economic boundaries. The obstacles that play a dominant part in determining how refrigerant-nanofluid methods can be put into practice are outlined in this section [13].

6.1. Nanoparticle Stability and Agglomeration

The major limitation of the usage of nanofluid is the stability of nanoparticles. The Van der waals forces plays very important role. Al_2O_3, CuO, TiO_2, derivatives of graphene nanoparticles agglomerate over time. Agglomeration does alter thermophysical properties significantly, reduces the work of heat transfer, and causes plugging in minor passages of heat exchangers. In order to improve the stability of the nanofluid, various techniques can be used, such as surfactants, surface functionalization or ultrasonic dispersion. The major drawback of these processes involves the higher cost and the complexity [8].

6.2. Material Compatibility

One of the issues in using the nanoparticles in the refrigerant is the compatibility with the system material. The other issue with the nanoparticles is wear and tear of the moving components, such as compressor valves and seals, which are particularly related with shape, size and chemical activity. In addition, the other issue with the nanoparticle is improving the corrosiveness of the system. When these nanoparticles are exposed to polymeric seals, aluminium fins or copper tubes, especially the risk of corrosion also increases. These problems may undermine the reliability of the system and augment the routine of maintenance, which demeans the anticipated advantages of nanofluid-enhanced refrigerants [15].

6.3. Safety Concerns

The safety of novel refrigerant-nanofluid mixtures should be of particular interest. R32 and R1234yf are both of a mildly inflammable type (type A2L as per the ASHRAE standards). Although they are much safer than highly flammable refrigerants, one cannot underestimate the possibility of ignition, particularly when mixed with nanoparticles that can potentially change thermal Conductivity and combustion. Additionally, there is a lack of research on the effects of nanoparticles on the flammability threshold or toxic byproducts in accidental release or fires. Therefore, they need a large amount of safety testing and regulatory assessment before large-scale use [26].

7. Future Research Directions

Despite the significant advancements made in nanofluid-assisted refrigeration systems, there remain certain areas that still require further investigation to ensure that this technology can be utilized on a large scale and adopted by the industry.
Another area where research is needed is the development of a hybrid nanofluid. Another approach could be to combine multiple types of nanofluids, thereby enhancing their stability, thermal Conductivity, and viscosity. Another potential area could be the long-term stability and reliability of nanofluids. The studies conducted thus far have been limited in scope, and the available data regarding sedimentation, agglomeration, and chemical compatibility are extremely limited. Another potential area requiring further research is system-level optimization.

8. Conclusion

The move to low-GDP refrigerants is now a World Issue in the refrigeration and air conditioning industry, thanks to the environmental laws in the Montreal Protocol and the Kigali Amendment. Out of the set of options, R32 and R1234yf have become the top favourable ones to be chosen: they provide a good balance between sustainability in environmental aspects and thermodynamic efficiency. With the average level of flammability, R32 offers a fairly high performance. Whereas R1234yf, with ultra-low GWP, has received much interest in automotive and stationary air conditioning. All these refrigerants are a step towards lessening the climatic effect of vapor compression systems in comparison with their older counterparts, such as R134a and R410A.

In line with this, the naofluids have shown significant potential when these next level refrigerant is considered. The coefficient of performance of the system, heat transfer, and thermal Conductivity of the system can be significantly improved with the usage of nanoparticles such as Al_2O_3, TiO_2, CuO, and carbon-based additives. The nanofluid also contributed to improve the performance of the compressor reduces the energy losses. This practice also saves the energy of the residential AC systems.

References

[1] Carlos G. Albà et al., "Assessment of Low Global Warming Potential Refrigerants for Drop-in Replacement by Connecting Their Molecular Features to Their Performance," *ACS Sustainable Chemistry & Engineering*, vol. 9, no. 50, pp. 17034-17048, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[2] Nihar Shah et al., "*Opportunities for Simultaneous Efficiency Improvement and Refrigerant Transition in Air Conditioning*," UC Berkeley, pp. 1-109, 2017. [Google Scholar] [Publisher Link]

[3] M.E. Uwadiae, M.A. Akintunde, and T.I. Ogedengbe, "Experimental Investigation of R-134a and R-600a Refrigerant Blend in Domestic Vapour Compression Refrigeration System," *Nigerian Journal of Technology*, vol. 36, no. 4, pp. 1138-1144, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[4] E.E. Anyanwu, and N.V Ogueke, "Activated Carbon/Refrigerant Combinations for Solar Refrigeration Application," *Nigerian Journal of Technology*, vol. 20, no. 1, pp. 53-60, 2001. [CrossRef] [Google Scholar] [Publisher Link]

[5] Abhishek Kumar et al., "A Comprehensive Review Regarding Condensation of Low-GWP Refrigerants for Some Major Alternatives of R-134a," *Processes*, vol. 10, no. 9, pp. 1-34, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[6] Aung Myat, Md Mashiur Rahman, and Muhammad Akbar, "Nanofluid-Enhanced HVAC&R Systems (2015–2025): Experimental, Numerical, and AI-Driven Insights with a Strategic Roadmap.," *Sustain.*, vol. 17, no. 16, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[7] V. Viljasoo et al., "Combined Air Conditioning for Heating Rooms and Improving of Indoor Climate," *Agronomy Research*, vol. 11, no. 2, pp. 487-494, 2013. [Google Scholar] [Publisher Link]

[8] S. Kumar, J. Cerny, and P. Kic, "Air-Conditioning in the Cabins of Passenger Cars," *Agronomy Research*, vol. l6, no. 5, pp. 2088-2096, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[9] Prabakaran Rajendran et al., "Experimental Studies on the Performance of Mobile Air Conditioning System Using Environmental Friendly HFO-1234yf as a Refrigerant," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 235, no. 3, pp. 731-742, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[10] T.S. Mogaji et al., "COP Enhancement of Vapour Compression Refrigeration System Using Dedicated Mechanical Subcooling Cycle," *Nigerian Journal of Technology*, vol. 39, no. 3, pp. 776-784, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[11] Hussein Togun et al., "Revolutionizing Battery Thermal Management: Hybrid Nanofluids and PCM in Cylindrical Pack Cooling," *Materials for Renewable and Sustainable Energy*, vol. 14, no. 2, pp. 1-44, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[12] Meibo Xing, Hongfa Zhang, and Cancan Zhang, "An Update Review on Performance Enhancement of Refrigeration Systems using Nano-Fluids," *Journal of Thermal Science*, vol. 31, no. 4, pp. 1236-1251, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[13] F. Onoroh, M. Ogbonnaya, and L.O. Agberegha, "Modelling of the Temperature Profile of Heat Sinks for a Thermoelectric Cooler Module," *Nigerian Journal of Technology*, vol. 41, no. 3, pp. 429-437, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] K.S. Shelke, U.S. Wankhede, and S. Shelare, "Thermoacoustic Cooling Performance Using Nylon 6 Stack Material of Varied Geometry and Blended Helium-Argon Gas," *Nigerian Journal of Technology*, vol. 44, no. 1, pp. 77-86, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[15] R. Saidur et al., "A Review on the Performance of Nanoparticles Suspended with Refrigerants and Lubricating Oils in Refrigeration Systems," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 310-323, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[16] Michał Sobieraj, "Development of Novel Wet Sublimation Cascade Refrigeration System with Binary Mixtures of R744/R32 and R744/R290," *Applied Thermal Engineering*, vol. 196, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[17] Sayem Zafar, Ibrahim Dincer, and Mohamed Gadalla, "Evaluation of Thermophysical Properties of Refrigerant Clathrates with Additives," *International Communications in Heat and Mass Transfer*, vol. 89, pp. 165-175, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[18] P. Kic, "Influence of Air-Conditioning on Dust Level in Drivers' Cabin During the Harvest of Grain," *Agronomy Research*, vol. 15, no. 3, pp. 745-750, 2017. [Google Scholar] [Publisher Link]

[19] D.V Cao, and P. Kic, "Analysis of Indoor Temperature in the Workshop Building During the Summer: A Pilot Study," *Agronomy Research*, vol. 165, no. 4, pp. 1-8, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[20] K. Veera Raghavalu, and Govindha Rasu, "Review on Applications of Nanofluids Used in Vapour Compression Refrigeration System for Cop Enhancement," *IOP Conference Series: Materials Science and Engineering*, pp. 1-8, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[21] Aly M. A. Soliman et al., "Performance Enhancement of Vapor Compression Cycle Using Nano Materials," *2015 International Conference on Renewable Energy Research and Applications (ICRERA)*, Palermo, pp. 821-826, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[22] Christian Lucas, and Juergen Koehler, "Experimental Investigation of the COP Improvement of a Refrigeration Cycle by Use of an Ejector," *International Journal of Refrigeration*, vol. 35, no. 6, pp. 1595-1603, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[23] Ankur Geete, Mamta Sharma, and Pranjal Shrimali, "Entropy Generation and Exergy Destruction Analyses for Vapour Compression Refrigeration System with Various Refrigerants," *SN Applied Sciences*, vol. 1, no. 7, pp. 1-12, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[24] Y.Y. Hsieh, and T.F. Lin, "Evaporation Heat Transfer and Pressure Drop of Refrigerant R-410A Flow in a Vertical Plate Heat Exchanger," *Journal of Heat and Mass Transfer*, vol. 125, no. 5, pp. 852-857, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[25] Shang Chen et al., "Impacts of Partial-Load Service On Energy, Exergy, Environmental and Economic Performances of Low-Temperature Compressed Air Energy Storage System," *Journal of Energy Storage*, vol. 32, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[26] Binbin Yu et al., "Evaluation of Low-GWP and Mildly Flammable Mixtures as New Alternatives for R410A in Air-Conditioning and Heat Pump System," *International Journal of Refrigeration*, vol. 121, pp. 95-104, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[27] Rendy Adhi Rachmanto et al., "Enhancing the Efficiency of Finned Photovoltaic Thermal Collectors Using Al_2O_3, CuO, and TiO_2 Nano-Fluids: A Comprehensive Study on Thermal and Electrical Performance Optimization," *International Journal of Heat & Technology*, vol. 43, no. 3, pp. 1045-1056, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[28] Shengshan Bi et al., "Performance of a Domestic Refrigerator using TiO_2-R600a Nano-Refrigerant as Working Fluid," *Energy Conversion and Management*, vol. 52, no. 1, pp. 733-737, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[29] Olayinka S. Ohunakin et al., "Experimental Investigation of TiO_2-, SiO_2- and Al_2O_3-Lubricants for a Domestic Refrigerator System using LPG as Working Fluid," *Applied Thermal Engineering*, vol. 127, pp. 1469-1477, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[30] Faizan Ahmed, "Experimental Investigation of Al_2O_3-Water Nanofluid as a Secondary Fluid in a Refrigeration System," *Case Studies in Thermal Engineering*, vol. 26, pp. 1-8, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[31] George Kosmadakis, and Panagiotis Neofytou, "Investigating the Effect of Nanorefrigerants on a Heat Pump Performance and Cost-Effectiveness," *Thermal Science and Engineering Progress*, vol. 13, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[32] Zafer Cingiz, "Experimental Energetic and Exergetic Performance Evaluation of Refrigeration Systems using Al_2O_3 and TiO_2 Nanoparticles Operating with HFO-1234yf Refrigerant," *Journal of Thermal Analysis and Calorimetry*, vol. 151, no. 7, pp. 6231-6249, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[33] N. Subramani, and M.J. Prakash, "Experimental Studies on a Vapour Compression System using Nanorefrigerants," *International Journal of Engineering, Science and Technology*, vol. 3, no. 9, pp. 95-102, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[34] Taliv Hussain et al., "Performance Improvement of Vapour Compression Refrigeration System using Al_2O_3 Nanofluid," *IOP Conference Series: Materials Science and Engineering*, vol. 377, pp. 1-6, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[35] Kristen Henderson et al., “Flow-Boiling Heat Transfer of R-134a-Based Nanofluids in a Horizontal Tube,” *International Journal of Heat and Mass Transfer*, vol. 53, no. 5-6, pp. 944-951, 2010. [CrossRef] [Google Scholar] [Publisher Link]
[36] M.A. Kedzierski, and M. Gong, “Effect of CuO Nanolubricant on R134a Pool Boiling Heat Transfer,” *International Journal of Refrigeration*, vol. 32, no. 5, pp. 791-799, 2009. [CrossRef] [Google Scholar] [Publisher Link]
[37] Sergio Bobbo et al., “Influence of Nanoparticles Dispersion in POE Oils on Lubricity and R134a Solubility,” *International Journal of Refrigeration*, vol. 33, no. 6, pp. 1180-1186, 2010. [CrossRef] [Google Scholar] [Publisher Link]
[38] sasei Unarine Casey Ndanduleni, Teboho Ramathe, and Zhongjie Huan, “Experimental Analysis of an R134a Refrigeration System Using POE/CuO Nanolubricant,” *Case Studies in Thermal Engineering*, vol. 78, pp. 1-17, 2026. [CrossRef] [Google Scholar] [Publisher Link]