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Environment-Friendly Refrigerants for Sustainable Refrigeration and Air Conditioning: A Review

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Abstract

Refrigeration and air conditioning systems play a vital role in our modern society, and refrigerants are integral components of these systems. Traditional refrigerants like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) have caused significant environmental concerns because of their role in ozone depletion and global warming. Consequently, interest has increased in developing and implementing environmentally benign refrigerants possessing minimal global warming potential (GWP) and no ozone depletion potential (ODP). This review explores the emerging field of environment-friendly refrigerants such as natural refrigerants (NH_3, CO_2, hydrocarbons), hydrofluoroolefins (HFOs), hydrofluoro carbons (HFCs) with ultra-low GWP, hydrofluoroethers (HFEs) and mixtures or blends of these refrigerants. The article also compares their thermophysical, thermodynamic, environmental and safety properties, and their suitability for different applications. The key recommendations encompass the promotion of natural refrigerants, including NH3, CO2, and hydrocarbons, exhibit minimal environmental effects. Additionally, the exploration of HFOs and HFCs with ultra-low GWP and their mixtures as potential substitutes is advised. Transitioning to environment-friendly refrigerants is essential for achieving sustainable refrigeration and air conditioning systems, mitigating climate change, and ensuring the long-term viability of cooling technologies while preserving the environment.

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Introduction

Refrigeration and air conditioning systems play a vital role in numerous industries, such as food preservation, healthcare, comfort cooling, and industrial operations. These systems utilize refrigerants for heat transfer and cooling.[1] Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) were historically extensively used as refrigerants due to their favourable properties, including stability, minimal toxicity, and high energy efficiency. However, the discovery of their negative environmental effects has necessitated the development of substitute refrigerants.[2,3] It has been determined that CFCs and HCFCs contribute to ozone depletion and global warming by releasing chlorine and bromine atoms into the stratosphere. The Montreal Protocol, which was implemented in 1987, aimed to eradicate the production and consumption of substances that contribute to the depletion of the ozone layer.[4–6] The major environmental protection-related agreements related to refrigerants are shown in Table 1. The Montreal Protocol and the Kyoto Protocol have been implemented to address environmental issues such as ozone layer depletion and global warming. The Kigali Amendment to the Montreal Protocol was adopted in 2016 to phase down HFCs. The need to resolve the environmental impact of conventional refrigerants and comply with international regulations motivates the development of environmentally benign refrigerants.[7,8] The search for alternative refrigerants with reduced environmental impact is motivated by a number of significant factors, including ODP, GWP, Safety Considerations and Thermodynamic properties.

Table 1: Environment protection-related agreements for refrigerants

Agreement	Year	Major Results
Montreal Protocol	1987	Gradual elimination ozone-depleting substances (ODSs). To phase out CFC
Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC)	1997	Reduction of greenhouse gas emissions
Paris Agreement	2015	To phase out CFCs
Kigali Amendment to the Montreal Protocol	2016	Phase-down of hydrofluorocarbons (HFCs) and HFOs introduced.

Ozone depletion is a significant environmental concern because it increases the penetration of the sun's hazardous ultraviolet (UV) radiation, which can have negative effects on human health and ecosystems.[9,10] Environmentally beneficial refrigerants should have low or no ozone depletion potential (ODP), thereby minimizing ozone depletion.[11,12] Global warming potential is the ability of a substance, relative to carbon dioxide (CO_2), to retain heat in the atmosphere over a specific time period. The high GWP values of traditional refrigerants, including CFCs and HCFCs, contribute to the greenhouse effect and climate change. In order to mitigate their effect on global warming, environmentally beneficial refrigerants should have a significantly lower GWP.[13,14]

In addition to environmental considerations, the safety of refrigerants is of the utmost importance. Some conventional refrigerants are extremely toxic or combustible, posing hazards to human health and safety. To ensure safe operation in refrigeration and air conditioning systems, environmentally benign refrigerants should exhibit lower toxicity and lower flammability.[15] The efficacy and performance of refrigeration and air conditioning systems are directly affected by the thermodynamic properties of refrigerants. To ensure efficient and dependable operation, environmentally friendly refrigerants must possess desirable thermodynamic properties, such as appropriate boiling and condensing temperatures, heat transfer coefficients, and volumetric capacity.[16]

The background of the research conducted in this review article is based on the following premises

- Refrigeration and air conditioning are essential for numerous applications, including industrial operations, comfort cooling, medicinal storage, and food preservation.
- The use of conventional refrigerants in these systems has negative effects on the environment, including ozone depletion and global warming.
- There is a demand for environmentally friendly refrigerants with good thermophysical, thermodynamic, environmental and safety characteristics as well as minimal or negligible ODP and GWP. These properties influence the performance and acceptability of environment friendly refrigerants.
- Based on their chemical composition, environmentally friendly refrigerants can be divided into natural and synthetic categories.
- The introduction and deployment of environmentally friendly refrigerants in refrigeration and air conditioning systems present numerous challenges and opportunities.

Methodology

This review study examines the emerging field of environmentally friendly refrigerants. Firstly, environmental impact of traditional refrigerants is discussed. The second part is an overview of the criteria for choosing environmentally friendly refrigerants. The third part reviews the applications of environmentally friendly refrigerants that comprise natural refrigerants (NH_3, CO_2, hydrocarbons), hydrofluoroolefins (HFOs), ultra-low GWP hydrofluorocarbons (HFCs), hydrofluoroethers (HFEs), and combinations or blends of these refrigerants. The next section of the paper focuses on emerging technologies, aim to develop alternatives that are more efficient, environmentally sustainable, and energy-conserving. In subsequent section safety Safety Considerations and Regulatory framework is discussed. Final section addresses the Challenges and future directions for implementation of environmentally friendly refrigerants.

Environmental Impact of Traditional Refrigerants

The capacity of a material to obliterate ozone molecules in the stratosphere is referred to as ozone depletion potential. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), two common refrigerants, have been recognized as significant ozone depletion culprits. Chlorine atoms, which are present in CFCs, are discharged into the stratosphere once they reach the high atmosphere. When these chlorine atoms are released, they can catalytically destroy ozone molecules, causing the ozone layer to weaken. HCFCs nevertheless have the ability to deplete the ozone layer, although being less dangerous than CFCs. They have the ability to degrade ozone molecules since they include chlorine and fluorine atoms. To safeguard the ozone layer, the Montreal Protocol gradually phased out the manufacturing and use of CFCs and HCFCs.[16–18]

Also, traditional refrigerants, have high GWP values, including CFCs and HCFCs. In contrast to carbon dioxide (CO2) over a given time period, CFC-12, which is frequently used in older refrigeration systems, has a GWP of 10,900, suggesting that it significantly contributes to global warming. Despite having lower GWP values than CFCs, HCFCs nevertheless have an impact on global warming. A common refrigerant with a GWP of 1,810 is HCFC-22. These high GWP values highlight the need for alternative refrigerants with lower global warming potential.[19,20]

Environmentally Friendly Refrigerant Selection Criteria

Ozone Depletion Potential (ODP)

The ODP of a refrigerant is one of the most important criteria for ecologically acceptable refrigerants. ODP gauges a substance's capacity to annihilate stratospheric ozone molecules. The less hazardous a refrigerant is to the ozone layer, the lower its ODP value. In order to have a minimum or zero ODP, environmentally friendly refrigerants should be used.[21]

Global Warming Potential (GWP)

Another important factor for selecting ecologically friendly refrigerants is GWP. The greenhouse warming potential (GWP) measures a substance's capacity to trap heat in the atmosphere of the planet and hence influence climate change. Low-GWP refrigerants aid in reducing the effect of air conditioning and refrigeration on global warming. GWP values for environmentally friendly refrigerants need to be considerably lower than those for conventional refrigerants like CFCs and HCFCs.[22]

Toxicity and Flammability

Beyond their effects on the environment, refrigerants are also subject to safety issues. When evaluating a refrigerant's appropriateness, toxicity and flammability are crucial factors. Refrigerants considered environmentally friendly should be less harmful and provide fewer threats to human health and safety. They should also have minimal flammability to enable safe operation in refrigeration and air conditioning systems.

To evaluate refrigerants' toxicity and flammability properties, extensive testing and assessment is done. While flammability is normally examined using flammability limits, ignition energy requirements, and flame propagation characteristics, toxicity is typically analyzed using exposure limits and associated health risks.[23,24]

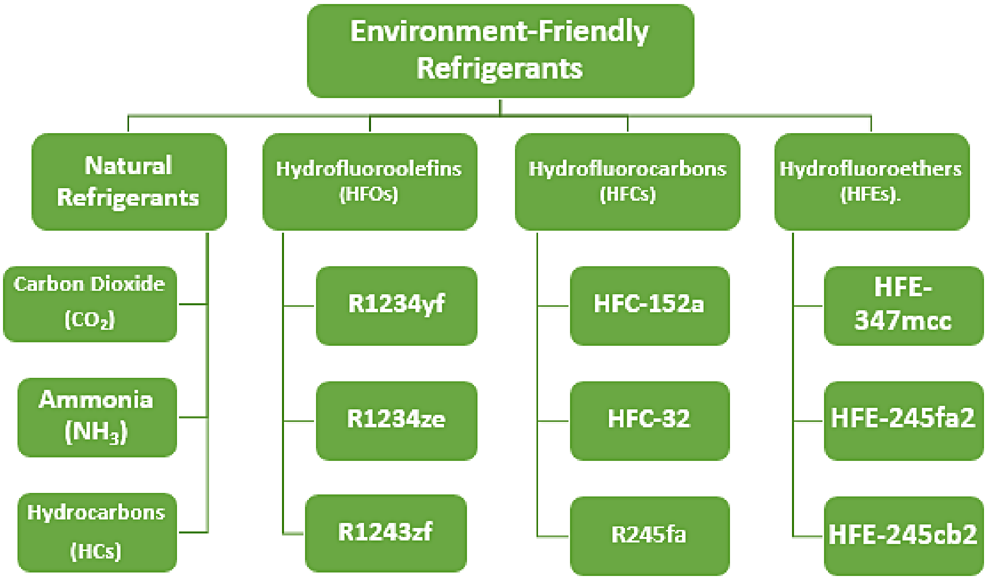

Fig. 1: Environment-Friendly Refrigerants.

Environmentally Friendly Refrigerants

Natural Refrigerants

Natural refrigerants have drawn much interest as safe substitutes for conventional refrigerants. They stand out for their minimal potential for global warming, non-ozone-depleting qualities, and low or no environmental effect. Ammonia (NH_3), hydrocarbons (HCs), and carbon dioxide (CO_2) are three frequently utilized natural refrigerants.[25]

Carbon Dioxide (CO_2)

Since many years ago, carbon dioxide (CO_2), a naturally occurring substance, has been utilized as a refrigerant. As a result of its zero GWP rating, it is a very ecologically friendly choice. Compared to conventional systems, CO_2 refrigeration systems run at greater pressures, which might create certain design and safety concerns. However, technological developments have improved the effectiveness and viability of CO_2 systems for a range of uses, including industrial refrigeration, cold storage, and supermarkets.[26]

Because it is inexpensive, non-toxic, and inflammable, CO_2 is a secure option for refrigeration applications. A further factor in the sustainability of the industry is the CO_2 byproduct, which may be trapped and used as a refrigerant.

Ammonia (NH_3)

Another popular natural refrigerant with outstanding thermodynamic qualities is ammonia (NH_3). It is one of the most ecologically responsible alternatives because it has no ozone depletion potential and a GWP value of 0. For many years, NH_3 has been employed in large-scale air conditioning, cold storage, and industrial refrigeration. Ammonia is extremely energy-efficient, has great heat transport capabilities, and uses little power. Ammonia is poisonous, thus, it must be handled carefully and with safety measures to guarantee proper functioning. Ammonia dangers must be managed with the use of proper system design, leak detection, and ventilation.[27]

Hydrocarbons (HCs)

Propane (R-290) and isobutane (R-600a), two hydrocarbons (HCs) that are naturally occurring substances, are low-GWP and ozone-depleting refrigerants. Small household refrigeration systems, vending machines, and commercial refrigeration equipment often employ HCs. They are very energy efficient and have good thermodynamic characteristics. Although hydrocarbons are extremely effective and have little influence on the environment, they are combustible and need for special safety precautions. To guarantee the secure use of hydrocarbon refrigerants, proper system design is required, including trustworthy leak detection and ignition prevention techniques.[28–30]

Hydrofluoroolefins or HFOs

A novel family of refrigerants called hydrofluoroolefins (HFOs) has gained appeal as an alternative to conventional refrigerants that is less harmful to the environment. HFOs are made with strong thermodynamic characteristics while having a low global warming potential (GWP). The HFOs 1234yf and 1234ze are two HFOs that are often utilized.31 The necessity to solve the environmental issues with conventional refrigerants, especially those with high GWP, led to the invention of HFOs. In an effort to lessen greenhouse gas emissions and slow down climate change, HFOs were created. GWP is significantly lower for these refrigerants than it was for their predecessors, such as hydrofluorocarbons (HFCs). HFOs were created in an effort to balance performance and environmental effects. In accordance with worldwide legislation and activities focused on decreasing greenhouse gas emissions, HFOs minimize the impact of refrigeration and air conditioning systems to global warming by lowering the GWP.[32–34]

HFOs have advantageous performance traits that make them suited for a range of uses. They have thermodynamic characteristics that are comparable to those of conventional refrigerants, enabling effective heat transmission and cooling. In refrigeration and air conditioning systems, HFOs also work well with the current machinery and lubricants, minimizing the need for significant transitional alterations. HFOs are created with minimal toxicity and either nil or low flammability in mind when it comes to safety. As a result, there are potentially fewer threats to human health and safety when using conventional refrigerants. To maintain safe operation and avoid any mishaps, it is still crucial to handle HFOs with the proper safety precautions and to adhere to approved recommendations.

When working with HFOs, proper system design, including leak detection and maintenance, is essential to ensuring their safe and effective usage. To reduce any possible dangers, it is advisable to adhere to the standards and instructions provided by manufacturers and regulatory agencies for the safe handling and use of HFOs.[35,36]

Hydrofluorocarbons (HFCs)

Synthetic refrigerants called hydrofluorocarbons (HFCs) were created to replace ozone-depleting compounds like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). HFCs possess a substantial GWP and actively contribute to the phenomenon of climate change. even if they do not destroy the ozone layer. To lessen their environmental effect, attempts have been undertaken to find low-GWP substitutes and blends/mixtures. Low-GWP HFC substitutes have been created in response to the demand for more ecologically acceptable refrigerants. These substitutes are designed to offer HFC-like thermodynamic features and performance with markedly less influence on global warming. HFC-32 (GWP of 675) and HFC-152a (GWP of 138) are two examples of low-GWP HFC substitutes. In comparison to conventional HFCs like HFC-134a (GWP of 1,430) and HFC-410A (GWP of 2,088), these substitutes offer a significant reduction in GWP while keeping effective cooling capabilities.[37–39] These refrigerants are suitable for various applications such as chillers, heat pumps, air conditioners and refrigerators.[40,41] A transitional road to more environmentally friendly refrigeration and air conditioning systems is made possible by the use of low-GWP HFC substitutes. By lowering greenhouse gas emissions linked to HFCs and adhering to international agreements and laws intended to lessen carbon footprint, they contribute to preventing climate change.

Blends and combinations have also been created to lessen the environmental effect of HFCs in addition to low-GWP HFC substitutes. These mixtures, which often include several refrigerants with complementing characteristics, enable for better performance and a lower GWP than individual HFCs. For instance, ozone-depleting chemicals have frequently been replaced by refrigerant mixes like R-407C and R-410A. Blends and combinations provide a balance between environmental factors, system compatibility, and energy efficiency. It is feasible to attain desirable qualities while lowering the GWP by blending several refrigerants. These precisely mixed refrigerants are designed for specific applications in order to maximize performance and guarantee safe operation. The environmental effect and safety of blends and mixes should still be assessed based on their composition, consumption, and application-specific needs even though they may have a lower GWP.

Hydrofluoroethers (HFEs)

These are synthetic refrigerants that have zero ODP and low to medium GWP. They are also non-flammable and have good thermal stability and compatibility with materials. Some examples of these refrigerants are R-E347mcc, R-E245fa2 and R-E245cb2. These refrigerants are mainly used as solvents, blowing agents and heat transfer fluids, but they can also be used as refrigerants for low-temperature applications.[42–44]

Table 2: Environmentally Friendly Refrigerants Properties, GWP, ODP and Applications

Refrigerant	Type	Properties	GWP	ODP	Applications	Reference
R717 (ammonia)	Natural	High efficiency, high toxicity, high flamma -bility, low cost	0	0	Industrial refrigeration, heat pumps, chillers	45–48
R744 (carbon dioxide)	Natural	High efficiency, high pressure, low toxicity, low flammability, low cost	1	0	Supermarket refriger -ation,heat pumps, transport refrigeration	
R290 (propane)	Natural	High efficiency, low pressure, low toxicity, high flammability, low cost	3	0	Domestic refrigeration, commercial refrigeration, air conditioning	
R1234yf (HFO-1234yf)	HFO	Low efficiency, low pressure, low toxicity, low flammability, high cost	4	0	Automotive air conditio -ning, chillers	49–51
R1234ze (HFO-1234ze)	HFO	Low efficiency, low pressure, low toxicity, low flammability, high cost	6	0	Commercial refrigeration, air conditioning	
R32 (HFC-32)	HFC	Medium efficiency, medium pressure, low toxicity, non-flammable, medium cost	677	0	Automotive air conditio -ning, domestic refrigeration	52–55
R152a (HFC 152a)	HFC	High efficiency, high pressure, low toxicity, non-flammable, med-ium cost	138	0	Air conditioning	

R-E347mcc (HFE-347mcc)	HFE	Low efficiency, low pressure, low toxicity, non-flammable, high cost, low heat of vaporization, medium specific volume, low thermal conductivity, high Prandtl number	9.5	0	Solvent, blowing agent, heat transfer fluid	56,57
R-E245fa2 (HFE-245fa2)	HFE	Low efficiency, low pressure, low toxicity, non-flammable, high cost, medium heat of vaporization, medium specific volume, low thermal conductivity, high Prandtl number	9.7	0	Solvent, blowing agent, heat transfer fluid	
R-E245cb2 (HFE-245cb2)	HFE	Low efficiency, low pressure, low toxicity, non-flammable, high cost, medium heat of vaporization, medium specific volume, low thermal conductivity, high Prandtl number	10.1	0	Solvent, blowing agent, heat transfer fluid	

Mixtures and Blends of Environmentally Friendly Refrigerants

In recent years, there have been several research conducted to explore the utilization of mixtures and blends as a means to enhance the performance of environmentally friendly refrigerants. Padmavathy *et al*[58] evaluates low-GWP refrigerants as environmentally friendly alternatives to R134a in low-temperature applications. Comparatively analyzing operational efficiency of R1234ze/R134a, R1234yf/R134a, R1234ze/R32, and R1234yf/R32, aims to identify sustainable alternatives. The 90:10 blend of R1234ze and R134a showed superior performance, making it a viable option for lower-temperature applications. Mohanraj & Abraham[59] studied eco-friendly refrigerant options for automobile air conditioners, including HFCs, HFOs, hydrocarbons, CO_2, composite mixed refrigerants, and nano refrigerants. Hydrocarbon refrigerants are recommended due to their favorable properties. The utilization of natural refrigerants and their mixtures by Mohapatra *et al*.[60] has been observed to be a successful strategy in mitigating the negative environmental impacts linked to chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants. This adoption not only enhances the dependability and durability of refrigeration systems but also helps to protect the environment.

In a study conducted by Kumma *et al*[61] it was reported that low GWP refrigerant mixtures are potential replacements for traditional R134a and R22 refrigerants in compact refrigeration units. These mixes are non-flammable, have zero ozone depletion potential, and have low global warming potential. Natural refrigerants and combinations mitigate environmental consequences associated with CFC and HCFC refrigerants, enhancing refrigeration systems' dependability and durability while protecting the environment. To mitigate environmental impacts, it is crucial to use refrigerants with low GWP and enhanced energy efficiency. However, many zero-ODP and low GWP alternatives have unfavorable attributes, such as increased flammability, toxicity, or reduced volumetric capacity. The study conducted by Uddin & Saha[62] recommends that HFC and HFO mixtures, specifically R32/R1234yf, R32/R1234ze, and R32/R1123, show potential as viable alternatives for replacing existing refrigerants. The study also reported that R744/R32/R1234ze(E) and R744/R32/R1234yf as favourable ternary refrigerant mixtures.

Farooq *et al* [63] studied HFO refrigerants and reported that R1234ze(Z) exhibits desirable thermodynamic properties, as evidenced by its low Global Warming Potential (GWP) value of 7. Consequently, it can be considered as a viable substitute refrigerant for refrigeration systems, contributing to the promotion of environmental sustainability. Another study was undertaken by Nair[64] on the topic of HFO refrigerants reported that compared to the coefficient of performance (COP) seen with R134a, the operational efficiency of environmentally friendly refrigerants R1234yf and R1234ze(E) in practical refrigeration systems showed a modest loss in COP. However, HFO-R1234yf has been recommended as a feasible alternative to R134a. Bhatti *et al*[65] found that the incorporation of environmentally friendly refrigerants in vapour absorption technology, which harnesses waste heat from engines, offers several benefits in terms of energy preservation for cooling systems and contributes to the reduction of greenhouse gas emissions.

For sustainable refrigeration and air conditioning, hydrofluoroolefins (HFOs) and natural refrigerants having potential, in reducing greenhouse gas emissions within the refrigeration and air conditioning sector. The examples of cities and countries that have adopted or expressed their intention to adopt different environment friendly refrigerants, such as New York City, California, Japan, China, India, and Europe. Furthermore, it has been established that refrigerant blends demonstrate non-flammability, possess an ODP of zero, and possess low levels of GWP. The application of natural refrigerants and their mixtures has been observed to yield significant benefits in terms of minimizing the environmental impacts linked to chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants. The implementation of this approach not only contributes to the improvement of reliability and longevity in refrigeration systems, but also plays a crucial role in preserving and protecting the environment.[66]

Emerging Technologies and Refrigerants

Several cutting-edge technologies and refrigerants are being investigated as the need for ecologically friendly refrigerants rises. The goal of these technologies is to create substitutes that are more effective, environmentally friendly, and energy efficient. Phase-change materials (PCMs), nano refrigerants, and ionic liquids are three noteworthy new technologies in this area.

Ionic liquids

A type of salts known as ionic liquids may be found at room temperature in a liquid condition. Considering their special qualities, such as low vapour pressure, good thermal stability, and little volatility, they have been researched as prospective refrigerants. Ionic liquids have the potential to be utilized in heat pumps, adsorption and absorption refrigeration systems. Ionic liquids are non-flammable, have low toxicity, and have a low impact on the environment when used as refrigerants. Additionally, because of their adjustable features, refrigerants may be created with the appropriate properties for certain applications. But in order to use ionic liquids as refrigerants more widely, issues including high cost, limited availability, and compatibility with current equipment must be resolved.[67–72]

Phase-Change Materials (PCMs)

Phase-change materials (PCMs) are substances that, when heated to a specified temperature, may change their phase (solid-liquid or liquid-gas) and store and release thermal energy. The use of PCMs for thermal energy storage in a variety of sectors, such as air conditioning and refrigeration, has been investigated. PCMs may be included in refrigeration and air conditioning systems to improve energy efficiency and lower peak load demand. PCMs can assist in controlling temperature variations and lowering the system's total energy consumption by storing and releasing thermal energy throughout the phase change process. The choice of suitable PCM for a refrigeration purpose relies on a number of variables, including the intended operating temperature range, heat transfer properties, and system compatibility. The goal of ongoing research is to create PCMs with enhanced thermal and durability characteristics to maximize their performance in refrigeration systems.[73–79]

Nano Refrigerants

A relatively recent and promising advancement in the refrigeration industry is the use of Nano refrigerants. They are made up of nanoparticles that are scattered throughout conventional refrigerants. The thermal characteristics of the refrigerant, such as thermal conductivity and heat transfer coefficients, can be improved by the nanoparticles, which are frequently metallic or oxide-based. The performance and energy efficiency of refrigeration systems can be increased by adding nanoparticles to refrigerants. It is possible for nano refrigerants to increase heat transfer rates, lower refrigerant charges, and boost system dependability. Additionally, by enhancing system performance and lowering energy usage, they can help to reduce the overall impact on the environment. Although nano refrigerants have potential, further study is required to determine their long-term stability, safety issues, and environmental effect. The potential advantages of nano refrigerants must be carefully weighed against any potential hazards and difficulties in their actual application.[80–87]

Safety Considerations and Regulations

The selection and implementation of ecologically friendly choices heavily depend on the safety issues around refrigerants. This section examines the flammability and toxicity issues associated with refrigerants, as well as the safety requirements and installation guidelines, as well as the regulatory frameworks and phase-out timetables in place.

Risks of Flammability and Toxicity

For safe operation, refrigerants' potential for toxicity and flammability must be thoroughly assessed. While toxicity deals with a substance's potential negative effects on human health and the environment, flammability refers to a substance's capacity to ignite and maintain burning. When handling, storing, and installing flammable refrigerants, such as hydrocarbons (HCs) and some low-GWP HFC substitutes, extra safety measures must be taken. To reduce the dangers associated with flammable refrigerants, adequate equipment, leak detection systems, and proper ventilation are required. Another major factor is toxicity. In high quantities, some refrigerants, such as ammonia (NH_3), can be poisonous. To guarantee worker and occupant safety, proper handling procedures, personal protection equipment, and adherence to suggested exposure limits are crucial. Implementing suitable safety measures and ensuring regulatory compliance need an understanding of the flammability and toxicity properties of refrigerants.[88–90]

Safety Codes and Standards

Refrigeration and air conditioning system design, installation, operation, and maintenance are all governed by safety standards and rules. Aspects including refrigerant choice, equipment design, leak detection, ventilation, and emergency response are covered by these standards and guidelines. Examples of widely accepted safety standards and codes include those created by groups like the International Electrotechnical Commission (IEC), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE), and the International Organisation for Standardisation (ISO). Specific criteria for refrigerant safety, system design, leak prevention, and emergency shutdown procedures are outlined in these standards and regulations. In order to minimise hazards to both human safety and the environment, refrigeration and air conditioning systems must be built and operated in accordance with safety regulations and rules.[91–94]

Regulatory Frameworks and Schedules for Phase-Out

At the national and international levels, regulatory frameworks and phase-out timelines are designed to control the use of ecologically hazardous refrigerants and encourage the switch to environmentally benign alternatives. The elimination of ozone-depleting compounds, such as CFCs and HCFCs, thanks to the Montreal Protocol, an international environmental accord, has significantly influenced the creation and uptake of more ecologically friendly substitutes. Many nations have developed rules and policies in addition to the Montreal Protocol to address the phase-out of high-GWP HFCs and promote the use of low-GWP substitutes. In order to encourage the switch to more environmentally friendly solutions, these rules place restrictions on the use, manufacturing, and importing of high-GWP refrigerants. To reduce the environmental effect and assure compliance, regulatory frameworks frequently contain measures for refrigerant management, leak detection, recovery, recycling, and safe disposal practices. To comply with legal requirements and promote environmental sustainability, it is crucial for players in the air conditioning and refrigeration business to be informed about the changing regulatory frameworks and phase-out timetables.

Challenges and Future Directions

Despite the advancements achieved in the creation of ecologically benign refrigerants, there are still many issues to be resolved. This section examines the future requirements for research and development as well as the technical difficulties and constraints, economic factors, and industry acceptance. The use of eco-friendly refrigerants might come with technological difficulties and restrictions. Certain refrigerants could differ thermodynamically from conventional ones, necessitating system modification and optimisation. For a smooth transfer, it is essential to take into account compatibility with current equipment, including compressors, seals, and lubricants. Alternative refrigerants may differ from conventional ones in terms of performance qualities, including dependability, capacity, and efficiency. A constant problem is achieving equivalent or better performance while still achieving environmental goals. Additionally, certain eco-friendly refrigerants, like natural refrigerants, have unique operating requirements, such high pressures or low temperatures, which may restrict their suitability for use in particular systems or regions. Researchers, engineers, and manufacturers will need to work together continuously to innovate and overcome these technological obstacles.

Economic factors drive the use of ecologically friendly refrigerants, but the expense of alternative refrigerants, equipment upgrades, and system retrofits can make it difficult for the industry to adopt them widely. To achieve economic viability, initial investment and long-term operational expenses must be thoroughly analysed, personnel and contractors may need additional training and certification, and accessibility and availability of alternative refrigerants and equipment can affect how widely they are used. Government incentives, legislation, and industry efforts may play a significant role in fostering the use of ecologically friendly refrigerants.

Research and development activities are necessary to advance the use of environmentally friendly refrigerants in the future. Areas that need more research include performance improvement, safety, materials compatibility, lifetime assessment, cost-cutting measures, and collaboration between academic, industrial, and governmental organisations. Performance improvement involves creating refrigerants with better thermodynamic properties, heat transfer characteristics, and system effectiveness. Safety involves conducting thorough evaluations of alternative refrigerants' flammability, toxicity, and long-term stability. Materials compatibility involves researching alternate refrigerants' compatibility with the materials used in refrigeration and air conditioning systems. Lifetime assessment involves carrying out thorough lifetime analyses of various refrigerants, encompassing manufacture, usage, and disposal phases. Cost-cutting measures involve investigating efficient production techniques and coming up with plans to bring down the price of equipment and refrigerants that are good for the environment.

Results

Based on the literature review, the results of the recent studies on environment friendly refrigerants are as follows.

- Ammonia, carbon dioxide, hydrocarbons are natural refrigerants that possess a negligible ODP and exhibit significantly lower or zero GWP when compared to their synthetic refrigerants. These refrigerants are widely acknowledged as being highly environmentally benign, as they have the capacity to significantly mitigate greenhouse gas emissions within the air conditioning and refrigeration industry. Natural refrigerants are commonly employed as substitutes for synthetic refrigerants in a wide range of refrigeration and air conditioning applications.
- Hydrofluoroolefins (HFOs) exhibit an ODP of zero and possess significantly lower GWP in comparison to hydrofluorocarbons (HFCs). They are being increasingly recognised as viable substitutes for hydrofluorocarbons (HFCs) in a range of refrigeration and air conditioning applications.
- Mixtures or blends of HFO and HFC, environmentally friendly refrigerants enhance the performance of environmentally friendly refrigerants.
- Ionic liquids, phase-change materials (PCMs), and nano refrigerants are examples of emerging technologies that have the potential to enhance

the effectiveness and efficiency of refrigeration and air conditioning systems.

- Safety factors must be taken into account when handling and employing environmentally friendly refrigerants, and compliance with safety standards and rules is essential.

Conclusion

In conclusion, the use of environmentally friendly refrigerants is crucial for sustainable and energy-efficient refrigeration and air conditioning systems. Based on this literature assessment, no refrigerant meets all technological and environmental criteria for sustainable refrigeration and air conditioning. Therefore, the selection of the best refrigerant depends on the specific application, system design, safety requirements, cost-effectiveness, and availability. The present literature review offers a complete examination of the existing research pertaining to environmentally sustainable refrigerants for the purposes of refrigeration and air conditioning. The comprehension of the merits and demerits of various refrigerants can aid researchers, manufacturers, policy makers, and consumers to make informed decisions on the best refrigerant for their specific application. Further investigation is required in order to formulate novel refrigerants that satisfy both technological and environmental prerequisites for the purpose of achieving sustainable refrigeration and air conditioning. Stakeholders may support a more environmentally friendly future while addressing the needs of cooling technologies by taking into account the environmental effect, safety, and energy efficiency of refrigerants.

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Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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