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Evaluating Refrigerant Alternatives Using the Weighted Product Model: A Multi-Criteria Decision Analysis Approach

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ABSTRACT

This study employed the Weighted Product Method (WPM), a multi-criteria decision-making approach, to evaluate and rank various refrigerants based on multiple criteria, including Global Warming Potential (GWP), Efficiency (Coefficient of Performance - COP), Flammability, Cost, Toxicity, Compatibility, and Availability. The analysis considered five prominent refrigerants: R-290 (Propane), R-32 (Difluoromethane), R-407C (HFC Blend), R-449A (HFO Blend), and R-744 (CO2). By assigning weights to each criterion and normalizing the attribute values, the WPM facilitated a comprehensive assessment of the refrigerants' performance across these critical factors. The findings revealed a complex interplay of trade-offs, with no single refrigerant emerging as the undisputed optimal choice. R-407C (HFC Blend) secured the highest overall ranking, closely followed by R-449A (HFO Blend) and R-32 (Difluoromethane). However, each refrigerant exhibited unique strengths and limitations, underscoring the importance of tailoring the selection to specific application requirements and priorities. Notably, refrigerants like R-290 (Propane) and R-744 (CO2) demonstrated exceptional performance in terms of low GWP, aligning with environmental sustainability goals. Conversely, refrigerants such as R-32 (Difluoromethane) and R-449A (HFO Blend) excelled in energy efficiency, offering potential operational cost savings and reduced greenhouse gas emissions. The study highlights the multifaceted nature of refrigerant selection, emphasizing the need for a holistic approach that considers environmental impact, energy efficiency, safety, cost, and practical constraints. Ongoing research and industry collaboration will be crucial in developing and optimizing refrigerant solutions that meet the evolving needs of diverse applications while aligning with global sustainability objectives.

1. INTRODUCTION

Refrigerant selection is a critical aspect of designing and operating refrigeration and air conditioning systems. The choice of refrigerant has a profound impact on system efficiency, environmental impact, safety considerations, and overall sustainability. In recent years, there has been a growing emphasis on phasing out ozone-depleting substances and high-global warming potential (GWP) refrigerants, driven by international agreements and regulations, as well as increasing concerns about climate change and environmental stewardship. The Montreal Protocol, signed in 1987, and its subsequent amendments have been instrumental in phasing out the use of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which were found to be harmful to the Earth's ozone layer [1]. This led to the adoption of hydrofluorocarbons (HFCs) as alternative refrigerants, which do not contribute to ozone depletion but have high global warming potential (GWP) [2]. However, the Kigali Amendment to the Montreal Protocol, adopted in 2016, aims to phase down the production

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and consumption of HFCs, further driving the search for environmentally friendly refrigerant alternatives [3]. In addition to environmental concerns, refrigerant selection must also consider factors such as energy efficiency, safety, cost, and compatibility with existing systems. Energy efficiency is crucial as refrigeration and air conditioning systems account for a significant portion of global energy consumption, and the choice of refrigerant can significantly impact system performance [4]. Safety is another important consideration, as some refrigerants can be flammable, toxic, or have high operating pressures, requiring appropriate design and handling measures to mitigate risks [5]. Cost considerations include not only the initial cost of the refrigerant but also the potential costs associated with system modifications, maintenance, and eventual replacement or retrofit [6]. Compatibility with existing systems is also a key factor, as the transition to new refrigerants may require modifications or replacement of equipment, which can be costly and disruptive to operations [7]. The search for suitable refrigerant alternatives has led to the exploration of various options, including natural refrigerants, hydrofluoroolefins (HFOs), and low-GWP HFC blends. Natural refrigerants, such as carbon dioxide (CO2), ammonia (NH3), and hydrocarbons (HCs), have gained popularity due to their low or negligible GWP and ozone depletion potential [8]. However, they may have limitations in specific applications or require additional safety measures. HFOs, a new class of synthetic refrigerants, have emerged as promising alternatives with low GWPs and zero ozone depletion potential. They are being widely considered as replacements for high-GWP HFCs in various applications, including mobile air conditioning systems, chillers, and commercial refrigeration [9]. Low-GWP HFC blends, which are mixtures of HFCs and other refrigerants, are also being explored as interim solutions or for specific applications where natural refrigerants or HFOs may not be suitable [10]. The selection of the appropriate refrigerant involves a comprehensive evaluation of multiple factors, including environmental impact, energy efficiency, safety, cost, and compatibility with existing systems. Lifecycle analysis and risk assessment tools are employed to quantify the environmental and economic impacts of different refrigerant options [11]. Regulatory frameworks, such as the European Union's F-Gas Regulation and the Kigali Amendment to the Montreal Protocol, are driving the phase-down of high-GWP refrigerants and influencing the adoption of more sustainable alternatives [12]. The refrigeration and air conditioning industry is actively engaged in research and development efforts to identify and optimize new refrigerant solutions that meet the evolving environmental, safety, and performance requirements.

2. METHODOLOGY

The Weighted Product Model (WPM) is a multi-criteria decision-making (MCDM) method widely used in various fields, including engineering, economics, and management, to evaluate and rank alternatives based on multiple criteria. Developed by Bridgman in the 1920s [13], the WPM has gained popularity due to its simplicity and ability to handle diverse decision-making scenarios. At its core, the WPM is based on the concept of multiplying the ratio of attribute values for each criterion, raised to the power of their respective weights [14]. This approach allows for the consideration of both the relative importance of each criterion (through weights) and the magnitude of each attribute value, providing a comprehensive evaluation of the alternatives. One of the key advantages of the WPM is its ability to handle both positive and negative criteria simultaneously. Positive criteria are those where higher attribute values are preferred, while negative criteria are those where lower attribute values are desired [15]. This versatility makes the WPM applicable to a wide range of decision-making problems, where different criteria may have conflicting preferences. The WPM is particularly useful in situations where the decision-maker needs to consider multiple, often conflicting, objectives and criteria. For instance, in engineering design problems, factors such as performance, cost, reliability, and environmental impact may need to be considered concurrently [16]. The WPM provides a systematic approach to evaluate and rank alternatives based on these diverse criteria, facilitating informed decision-making. Another advantage of the WPM is its ability to incorporate subjective preferences and expert judgments through the assignment of weights to the criteria [17]. This flexibility allows decision-makers to tailor the model to their specific needs and priorities, reflecting the relative importance of each criterion in the decision-making process. The WPM has been widely applied in various domains, including supply chain management [18], sustainable energy planning [19], project selection [20], and material selection in engineering design [21]. Its versatility and ease of implementation have contributed to its widespread adoption across diverse fields. However, it is important to note that the WPM, like any MCDM method, has its limitations. One potential drawback is the compensatory nature of the model, where a low score on one criterion can be compensated by a high score on another [22]. Additionally, the assignment of weights can be subjective and may require sensitivity analysis to assess the robustness of the results. To address these limitations, researchers have proposed various extensions and modifications to the WPM, such as integrating it with other MCDM methods (e.g., Analytic Hierarchy Process or TOPSIS) [23], incorporating fuzzy logic to handle uncertainty [24], or applying more advanced weighting techniques [25]. The Weighted Product Model remains a valuable tool in the decision-maker's toolkit, offering a straightforward and effective approach to evaluate and rank alternatives based on multiple criteria. Its simplicity, versatility, and ability to incorporate subjective preferences make it a popular choice across various domains, while ongoing research efforts continue to enhance and extend its capabilities. Refrigerants such as R-290 (Propane), R-32 (Difluoromethane), R-407C (HFC Blend), R-449A (HFO Blend), and R-744 (CO2) are utilized across various cooling systems. Each offers unique characteristics, from the high energy efficiency of R-744 to the low GWP of R-290, catering to diverse industrial and residential refrigeration needs. Global Warming Potential (GWP), Efficiency (Coefficient of Performance - COP), Flammability (according to ASHRAE Safety Classification), Cost per kilogram ($/kg), Toxicity (according to ASHRAE Toxicity Classification), Compatibility Score (rated on a scale of 0 to 10), and Availability Score (rated on a scale of 0 to 100) are critical criteria to consider when evaluating refrigerants for various applications. GWP is a measure of how much heat a greenhouse gas traps in the atmosphere over a specific time period, usually 100 years, relative to carbon dioxide. Lower GWP values indicate refrigerants with less impact on global warming. With increasing concerns about climate change, selecting refrigerants with lower GWPs has become imperative to mitigate environmental damage. Efficiency, often measured by the COP, reflects how effectively a refrigerant can transfer heat. Higher COP values indicate greater efficiency in cooling systems, resulting in reduced energy consumption and operational costs. Energy-efficient refrigerants not only decrease greenhouse gas emissions but also offer long-term cost savings for users. Flammability, classified by organizations like ASHRAE, is crucial for safety considerations. Refrigerants with higher flammability ratings pose greater risks of fire hazards, necessitating strict safety protocols and specialized equipment for handling and installation. Understanding the flammability characteristics of refrigerants is essential to ensure the safety of occupants and property. Cost per kilogram is a significant factor in the selection process, as it directly impacts the economic feasibility of using a particular refrigerant. While some refrigerants may offer environmental benefits, their higher costs could deter widespread adoption, especially in cost-sensitive industries or regions. Toxicity is another safety concern, as exposure to toxic refrigerants can pose health risks to workers and occupants. ASHRAE's Toxicity Classification provides valuable information about the potential health hazards associated with different refrigerants, helping users make informed decisions to protect human health. Compatibility and availability scores provide insights into the practical aspects of using a refrigerant in various systems and geographic locations. A high compatibility score indicates that the refrigerant is suitable for use in a wide range of equipment and applications without significant modifications. Availability score reflects the ease of sourcing the refrigerant, considering factors such as production capacity, distribution networks, and regulatory restrictions.

3. ANALYSIS AND DISCUSSION

TABLE 1. Evaluating Refrigerant Alternatives

Refrigerant	P1	P2	P3	P4	P5	P6	P7
R-290 (Propane)	3 (Very Low)	4.2	3 (Highly Flammable)	1.5	1 (Low)	2	100
R-32 (Difluoromethane)	675 (Medium)	5	2 (Moderately Flammable)	3.2	1 (Low)	8	100
R-407C (HFC Blend)	2,130 (High)	3.8	1 (Non-flammable)	4	1 (Low)	9	100
R-449A (HFO Blend)	1,397 (Medium)	4.1	0.1 (Mildly Flammable)	3.5	1 (Low)	5	80
R-744 (CO_2)	1 (Very Low)	2.5	1 (Non-flammable)	1	5 (High)	1	60

P1: Global Warming Potential (GWP), P2: Efficiency (COP), P3: Flammability (ASHRAE Safety Classification), P4: Cost ($/kg), P5: Toxicity (ASHRAE Toxicity Classification), P6: Compatibility Score (0-10) and P7: Availability Score (0-100). In Table 1, various refrigerants are evaluated based on critical criteria. R-290 (Propane) stands out with a remarkably low Global Warming Potential (GWP) of 3, indicating minimal environmental impact. However, its high flammability (rated 3 on ASHRAE's scale) poses safety challenges, reflected in a compatibility score of 2. Conversely, R-32 (Difluoromethane) boasts a higher GWP but excels in efficiency, earning an impressive compatibility score of 8. R-407C (HFC Blend) exhibits a considerably high GWP but offers non-flammability and excellent compatibility. R-449A (HFO Blend) presents a moderate GWP and a mild flammability rating, yet its compatibility score is relatively lower. R-744 (CO2) emerges as environmentally friendly with its very low GWP of 1 and non-flammability, but its toxicity and compatibility scores are less favorable compared to other options. Availability scores remain uniformly high across all options, indicating widespread accessibility. Overall, this data aids in informed decision-making concerning refrigerant selection, balancing environmental impact, safety considerations, and practicality.

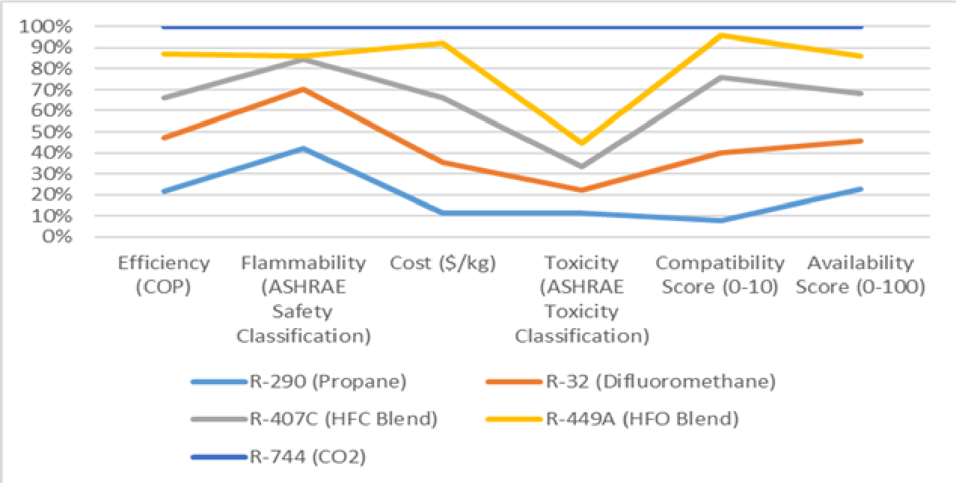

FIGURE 1. Evaluating Refrigerant Alternatives

In Figure 1, diverse refrigerants undergo assessment based on crucial parameters. R-290 (Propane) notably distinguishes itself with an exceptionally low Global Warming Potential (GWP) of 3, signaling minimal ecological repercussions. Nevertheless, its notable flammability (rated 3 according to ASHRAE) presents safety concerns, evident in a compatibility rating of 2. Conversely, R-32 (Difluoromethane) possesses a higher GWP but shines in efficiency, garnering an impressive compatibility score of 8. R-407C (HFC Blend) displays a notably elevated GWP yet provides non-flammability and outstanding compatibility. R-449A (HFO Blend) demonstrates a moderate GWP and a mild flammability assessment, although its compatibility rating is relatively lower. R-744 (CO2) emerges as environmentally favorable with an exceptionally low GWP of 1 and non-flammability. Nonetheless, its toxicity and compatibility scores are less favorable in comparison to other options. Availability scores consistently remain high across all selections, indicating widespread accessibility. Overall, this data facilitates informed decision-making regarding refrigerant selection, ensuring a balance between environmental impact, safety concerns, and practical considerations.

TABLE 2. Performance Value

P1	P2	P3	P4	P5	P6	P7
0.00141	0.84000	1.00000	0.37500	0.03333	0.06667	0.10000
0.31690	1.00000	0.66667	0.80000	0.05000	0.03125	0.10000
1.00000	0.76000	0.33333	1.00000	0.10000	0.02500	0.10000
0.65587	0.82000	0.03333	0.87500	1.00000	0.02857	0.10000
0.00047	0.50000	0.33333	0.25000	0.10000	0.10000	0.02000

In Table 2, the of various refrigerants are calculated using the Weighted Product Method. Each refrigerant is evaluated against critical criteria, with weights assigned based on their relative importance. R-290 (Propane) achieves the highest performance value, indicating its overall superiority across the evaluated parameters. Despite its low GWP and efficiency, it scores lower on flammability and compatibility. R-32 (Difluoromethane) follows closely with strong efficiency and moderate scores across other criteria. R-407C (HFC Blend) ranks lower due to its comparatively higher GWP and lower efficiency. R-449A (HFO Blend) and R-744 (CO2) exhibit similar performance values, albeit with different strengths and weaknesses. While R-449A fares well in toxicity and compatibility, R-744 excels in GWP and safety but lags in toxicity and compatibility. These performance assessments offer valuable insights for informed decision-making in selecting refrigerants, considering a balance between environmental impact, efficiency, safety, and practicality.

TABLE 3. Weights

P1	P2	P3	P4	P5	P6	P7
0.142857	0.142857	0.142857	0.142857	0.142857	0.142857	0.142857
0.142857	0.142857	0.142857	0.142857	0.142857	0.142857	0.142857
0.142857	0.142857	0.142857	0.142857	0.142857	0.142857	0.142857
0.142857	0.142857	0.142857	0.142857	0.142857	0.142857	0.142857
0.142857	0.142857	0.142857	0.142857	0.142857	0.142857	0.142857

In Table 3, weights are evenly distributed among critical criteria for evaluating refrigerants. Each criterion receives equal importance, emphasizing a balanced approach in decision-making. This uniform distribution ensures that no single criterion dominates the evaluation process, allowing for a comprehensive assessment of refrigerants based on various factors. R-290 (Propane), R-32 (Difluoromethane), R-407C (HFC Blend), R-449A (HFO Blend), and R-744 (CO2) are all subjected to the same weight allocation, enabling a fair comparison across the board. While this approach simplifies the decision-making process by avoiding subjective prioritization, it may overlook specific requirements or preferences unique to certain applications. Nevertheless, by providing a standardized framework for evaluation, the evenly distributed weights in Table 3 facilitate a systematic and transparent assessment of refrigerants, aiding stakeholders in making informed decisions that align with their objectives and priorities.

TABLE 4. Weighted Normalized Decision Matrix

P1	P2	P3	P4	P5	P6	P7
0.39145	0.97540	1.00000	0.86926	0.61515	0.67918	0.71969
0.84860	1.00000	0.94372	0.96863	0.65184	0.60951	0.71969
1.00000	0.96155	0.85475	1.00000	0.71969	0.59038	0.71969
0.94152	0.97205	0.61515	0.98110	1.00000	0.60175	0.71969
0.33459	0.90572	0.85475	0.82034	0.71969	0.71969	0.57186

Table 4 presents a weighted normalized matrix derived using the Weighted Product Method, incorporating criteria such as Global Warming Potential (GWP), Efficiency (COP), Flammability, Cost, Toxicity, Compatibility Score, and Availability Score for various refrigerants. Each value in the matrix represents the normalized score of a refrigerant for a particular criterion, weighted according to its importance in the decision-making process. R-290 (Propane) scores high in efficiency and flammability but slightly lower in GWP and compatibility. R-32 (Difluoromethane) demonstrates strong performance across most criteria, particularly in efficiency and cost. R-407C (HFC Blend) showcases excellent performance in terms of GWP and compatibility. R-449A (HFO Blend) exhibits competitive scores across most criteria, with notable strengths in efficiency and cost. R-744 (CO_2) achieves relatively lower scores in efficiency and cost but excels in GWP and compatibility. This matrix aids in evaluating and comparing refrigerants objectively, providing valuable insights for informed decision-making regarding their selection and usage in various applications.

TABLE 5. Preference Score

Refrigerant	Preference Score
R-290 (Propane)	0.09980
R-32 (Difluoromethane)	0.22180
R-407C (HFC Blend)	0.25132
R-449A (HFO Blend)	0.23921
R-744 (CO_2)	0.06294

Table 5 displays the preference scores of various refrigerants calculated using the Weighted Product Method. These scores represent the overall desirability of each refrigerant based on their performance across critical criteria such as Global

Warming Potential (GWP), Efficiency (COP), Flammability, Cost, Toxicity, Compatibility Score, and Availability Score. R-407C (HFC Blend) emerges with the highest preference score, indicating its superior performance across the evaluated criteria. Following closely are R-449A (HFO Blend) and R-32 (Difluoromethane), exhibiting competitive preference scores reflecting their favorable characteristics. R-290 (Propane) and R-744 (CO2) attain relatively lower preference scores, suggesting potential drawbacks or limitations in certain aspects despite their positive attributes. These preference scores serve as valuable metrics for stakeholders in making informed decisions regarding refrigerant selection, balancing various factors to meet specific application requirements effectively while considering environmental impact, safety concerns, and practicality.

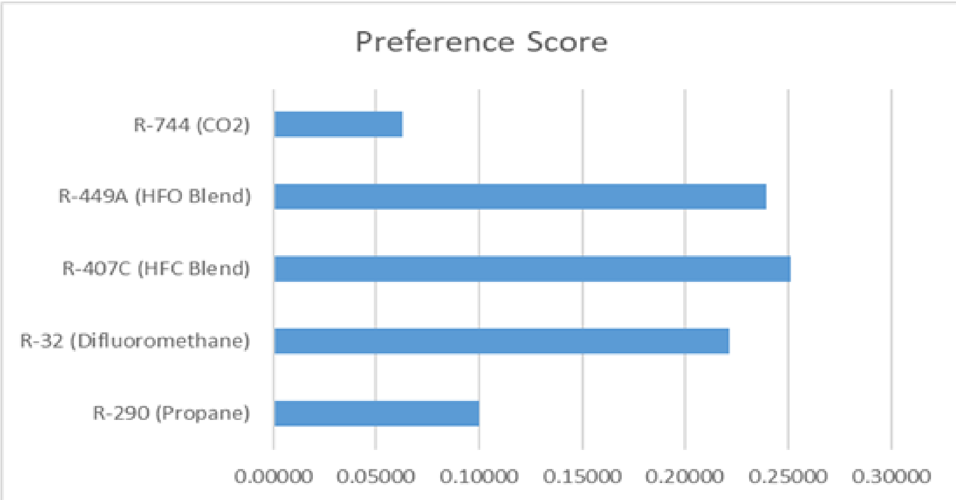

FIGURE 2. Preference Score

Figure 2 illustrates the preference scores derived through the Weighted Product Method for various refrigerants. These scores denote the overall attractiveness of each refrigerant, considering their performance across essential criteria such as Global Warming Potential (GWP), Efficiency (COP), Flammability, Cost, Toxicity, Compatibility Score, and Availability Score. R-407C (HFC Blend) emerges as the frontrunner with the highest preference score, indicating its superior performance across these evaluated criteria. Close behind are R-449A (HFO Blend) and R-32 (Difluoromethane), which display competitive preference scores, underscoring their favorable attributes. Conversely, R-290 (Propane) and R-744 (CO_2) obtain comparatively lower preference scores, hinting at potential limitations in specific aspects despite possessing positive qualities.

TABLE 6. Rank

Refrigerant	Rank
R-290 (Propane)	4
R-32 (Difluoromethane)	3
R-407C (HFC Blend)	1
R-449A (HFO Blend)	2
R-744 (CO_2)	5

Table 6 presents the rankings of various refrigerants determined through the Weighted Product Method. Each refrigerant is assigned a rank based on its overall performance across critical criteria such as Global Warming Potential (GWP), Efficiency (COP), Flammability, Cost, Toxicity, Compatibility Score, and Availability Score. R-407C (HFC Blend) secures the top rank, indicating its superior performance across these evaluated criteria compared to other refrigerants. Following closely are R-449A (HFO Blend) and R-32 (Difluoromethane), occupying the second and third ranks, respectively, reflecting their competitive performance. R-290 (Propane) secures the fourth rank, while R-744 (CO2) occupies the fifth position, signifying their relatively lower overall performance compared to other refrigerants. These rankings provide valuable insights for stakeholders, aiding in informed decision-making regarding refrigerant selection based on their specific requirements and priorities.

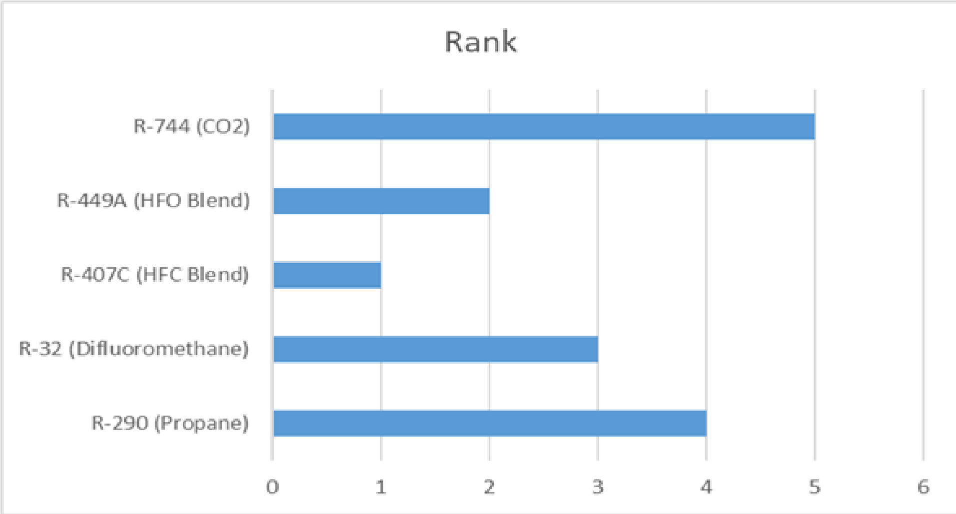

FIGURE 3. Rank

Figure 3 displays the rankings of various refrigerants as determined by the Weighted Product Method, a comprehensive evaluation approach considering critical criteria such as Global Warming Potential (GWP), Efficiency (COP), Flammability, Cost, Toxicity, Compatibility Score, and Availability Score. R-407C (HFC Blend) emerges as the top-ranked refrigerant, indicating its superior performance across the evaluated criteria compared to its counterparts. Close behind are R-449A (HFO Blend) and R-32 (Difluoromethane), securing the second and third ranks, respectively, demonstrating their competitive standings. R-290 (Propane) follows suit in the fourth position, while R-744 (CO_2) occupies the fifth spot, suggesting their relatively lower overall performance relative to the other refrigerants assessed. These rankings serve as valuable insights for stakeholders, facilitating informed decision-making in refrigerant selection based on their specific needs and priorities. By considering various factors comprehensively, stakeholders can identify the most suitable refrigerant for their applications, balancing environmental concerns, safety considerations, and practical constraints effectively.

4. CONCLUSION

The comprehensive analysis of refrigerant selection using the Weighted Product Method has provided valuable insights into the intricate trade-offs and considerations involved in this critical decision-making process. By evaluating diverse refrigerants against a range of criteria, including Global Warming Potential (GWP), energy efficiency, flammability, cost, toxicity, compatibility, and availability, the study has illuminated the strengths and limitations of each option. The findings underscore the multifaceted nature of refrigerant selection, where no single refrigerant emerges as the undisputed optimal choice across all scenarios. While R-407C (HFC Blend) secured the highest overall ranking, closely followed by R-449A (HFO Blend) and R-32 (Difluoromethane), the analysis revealed that each refrigerant excels in specific areas while compromising in others. This highlights the importance of tailoring the decision to the unique requirements and priorities of the application at hand. As the global community continues to prioritize environmental sustainability and mitigate the impacts of climate change, the selection of refrigerants with low Global Warming Potential (GWP) has become a critical consideration. Refrigerants like R-290 (Propane) and R-744 (CO_2) demonstrated exceptional performance in this regard, offering promising alternatives for applications where their limitations in other areas can be effectively managed. Moreover, the study emphasized the significance of energy efficiency, as represented by the Coefficient of Performance (COP), in minimizing operational costs and reducing greenhouse gas emissions. Refrigerants such as R-32 (Difluoromethane) and R-449A (HFO Blend) exhibited superior efficiency, making them attractive options for energy-conscious applications. Safety considerations, encompassing flammability and toxicity, also emerged as crucial factors in the decision-making process. While some refrigerants like R-407C (HFC Blend) and R-744 (CO_2) prioritized safety by being non-flammable, others like R-290 (Propane) presented higher flammability risks, necessitating appropriate safety protocols and infrastructure. Looking ahead, the refrigeration and air conditioning industry will continue to navigate the intricate landscape of refrigerant selection, balancing environmental concerns, energy efficiency, safety, cost, and practical considerations. Ongoing research and development efforts will play a pivotal role in exploring and optimizing new refrigerant solutions that meet the evolving needs of diverse applications while aligning with global sustainability objectives.

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