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Research Article

Evaluating the factors influencing the sustainable refrigerant selection by fuzzy decision making approach

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ABSTRACT

Considering that cooling in cooling systems is more costly than heating, the importance of refrigerant selection in cooling systems is even more obvious. Due to the complexity of the refrigerant selection problem, a multi-criteria decision approach must be used to implement a thorough and organized evaluation of the factors. The purpose of this study is to evaluate the criteria to be considered when choosing refrigerants using the interval type-2 trapezoidal fuzzy Analytic Hierarchy Process (AHP). As a result, the most important and least crucial refrigerant selection criteria are determined by calculating the weights and obtaining the ranking of the requirements. In this way, the refrigerant selection criteria are prioritized, and the most crucial factor in refrigerant selection has emerged as energy efficiency. In light of the results, it has become clear that it is now essential for everyone in the world to use environmentally friendly, highly effective refrigerants.

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1. INTRODUCTION

The global energy consumption of refrigeration and air conditioning is approximately 20% [1]. For this reason, refrigeration systems, including heat pumps, pulsating heat pipes [24, 25], refrigerators, HVAC (heating, ventilation, and air conditioning), etc., have vital importance in our daily and business lives. They help cool dwelling places, business offices, and meat, vegetables, and fruit products [2, 3]. The main component of refrigeration systems is refrigerants, which are working fluids that change phase from gas to liquid regularly. In the literature, there are two different classifications of refrigerants. The first is related to chemical compositions [4], and the second is about the progression of refrigerants from the past to now [5]. Refrigerants can be divided into five groups that are natural refrigerants, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), refrigerant blends, and hydrofluorocarbons (HFCs) [3, 4] in terms of chemical compositions.

The evolution of refrigerants from their invention to the future is shown in Figure 1 by dividing into four generations [5]. These are the first generation from 1830 to the 1930s, the second generation from 1931 to 1990s, the third generation from 1991 to 2010s, and the fourth generation from 2010 to now in terms of development of refrigerants in the long run. The first generation of refrigerants

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was used regardless of flammability, toxicity, and environmental impacts [1, 5]. In the second generation of refrigerants, the producer was taken into account the safety and durability of the refrigerants. HCFCs and CFCs are the refrigerant types commonly used in this generation. Third-generation refrigerants were developed to protect the ozone layer due to the requirement of the Montreal Protocol [6]. This protocol restricts the HCFCs and CFCs to achieve low ozone depletion potential (ODP). The fourth-generation refrigerants evolved because of concerns about the growing global warming after the Kyoto Protocol. According to this Protocol, countries must restrict or prohibit using the HFCs and PFCs types of refrigerants [3, 5]. In developing fourth-generation refrigerants, refrigerants with low/zero ODP, low global warming potential (GWP), and high efficiency have been developed and produced due to the increasing global warming concern.

The European Union (EU) Commission has restricted using HFC refrigerants due to their high global warming potential [7]. Hydrofluoroolefin refrigerants (HFO) present low/zero ODP and extremely low GWP due to the absence of no chlorine and a brief atmospheric period [8]. Hence, HFOs have great potential to be used as the fourth-generation refrigerant [9]. Along with developing or selecting the more eco-friendly refrigerant, other essential properties, such as sustainability, thermodynamic properties, flammability, etc., play an essential role in choosing a new refrigerant [10, 11]. Thermodynamic properties must be a high coefficient of performance (COP), thermal conductivity, vapor density, latent vaporization heat, low liquid viscosity, critical pressure, and liquid density to determine the suitable refrigerants in refrigeration systems. In selecting the appropriate refrigerant, it must have low/zero ODP [12], [13], low GWP [2, 3, 6, 10–12, 14–19], flammability [2, 3, 6, 10–12, 14, 15, 17–19], low secondary environmental impacts [2] and toxicity [2, 3, 10–12, 14, 15, 17, 19] in terms of environmental impacts. McLinden et al. [1] and Kaseeian et al. [2] prepared the required criteria list, including minimal flammability, low toxicity, GWP and secondary environmental impacts, zero ODP, long operational life, material compatibility, maximized recyclable content, maximum energy efficiency, reasonable cost, and stable for the life of the system for requirements for new refrigerants. In the study of Vuppaladadiyam et al. [3], they reviewed the development of refrigerants and their undesired environmental impacts. They mentioned ideal fourth-generation refrigerant properties such as zero ODP, low GWP, high efficiency, no toxicity, and no flammability. Abas et al. [4] researched the optimal refrigerant for low GWP and no ODP for the solar water heating system. Mohanraj and Abraham's review study [5] analyzed eco-friendly refrigerants for automobile air conditioners regarding thermophysical, thermodynamic, and chemical characteristics. Another review study by Bolaji and Huan [6] suggested natural refrigerants reduce the environmental impacts of the HFC, CFC, and HCFC refrigerants. Meng et al. [7] investigated the conditioning performance of a suggested R1234yf/R134a refrigerant having low GWP, no ODP, and no flammability for automobile air conditioner systems. Their suggested refrigerant helps to reduce the GWP impacts and eliminate the ODP and flammability. Direk et al. [8] experimentally investigated the performance of alternative refrigerants, R444A and R152a, in automobile air conditioner systems to reduce environmental impacts such as GWP and ODP. They found that R152a refrigerant significantly enhances the refrigeration performance compared to the R134a and R444A.

Table 1 summarizes the literature on refrigerant selection using different types of MCDM and machine learning methods. In the study of Poongavanam et al. [11], they found the optimum refrigerant for the automobile refrigeration system with the help of TOPSIS, MOORA, EDAS, and sensitivity analysis. Souayeh et al. [12] used MCDM methods like TOPSIS, EDAS, and MOORA to select environmentally friendly refrigerants in applying HVAC and renewable energy devices. Similarly, Ustaoğlu

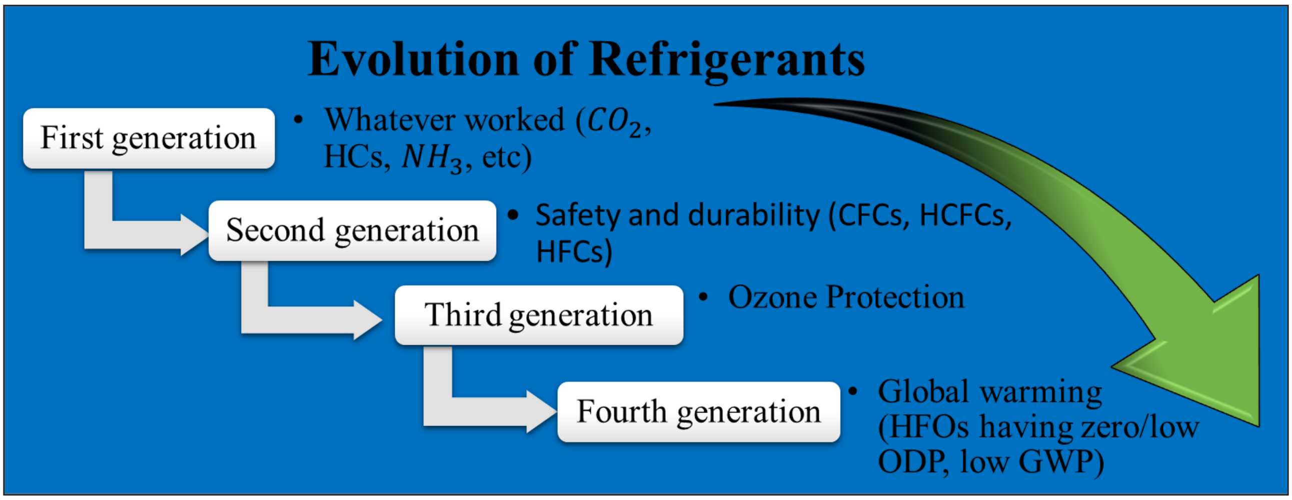

Figure 1. Evolution of refrigerants in time.

Table 1. Summary of literature related to refrigerant selection

Author(s)	Subject	Methods
Poongavanam et al. [11]	Refrigerant selection in the application of refrigeration systems for automobile	TOPSIS, MOORA, EDAS, and Sensitivity analysis
Devotta et al. [22]	Classification of refrigerant in terms of flammability	ANN, Random forest model
Souayeh et al. [12]	Eco-friend refrigerant selection in the application of HVAC and Renewable energy devices	TOPSIS, EDAS, MOORA
Prabakaran [23]	Optimization of future refrigerants for domestic refrigerant system	EDAS, Sensitivity analysis
Koundinya [21]	Selection of best refrigerant in terms of Environmental, Exergy, Economic, and Energy for heat pump	TOPSIS
Ustaoğlu et al. [20]	Refrigerant selection for vapor compression refrigeration cycle in terms of environmental, economic, safety, and cost	Taguchi, ANOVA, TOPSIS

et al. [20], for the vapor compression refrigeration cycle, and Koundinya and Seshadri [21] for the heat pump, selected the best refrigerant by using Taguchi, TOPSIS, and ANOVA and TOPSIS, respectively. On the other hand, Devotta et al. [22] performed a classification study for refrigerants regarding flammability with the help of ANN and the Random forest model.

Considering the sub-criteria mentioned above under main criteria such as thermodynamics, sustainability, and environmental, selecting the most suitable refrigerant for refrigeration systems is very challenging. At the same time, suitable refrigerants are determined using theoretical, simulation, and experimental methods, which take a long time and cost a lot of money [11]. Multi-criteria decision-making (MCDM) methods present a comprehensive selection and evaluation process considering different criteria for selecting eco-friendly, more efficient, and sustainable refrigerants. The need to consider many factors in the selection of refrigerants has made it possible to use the MCDM approach. Furthermore, it would be reasonable to use fuzzy logic to express the values that cannot be obtained numerically in the process and to model the uncertainty best. Based on all these important considerations, the problem of refrigerant selection is discussed in this paper, and a fuzzy MCDM approach is proposed to solve this problem. Besides, type-2 fuzzy sets, an extended version of fuzzy sets, handle uncertainty best and obtain results closest to the real world. As a result of detailed literature research, elements that should be considered in selecting the best refrigerant are determined, and then a prioritization analysis is performed to reveal the relative importance of these factors. For this purpose, the Analytic Hierarchy Process (AHP) method is utilized, which is an MCDM approach based on the pairwise comparison principle and is the most frequently used in the literature. As a result of this proposed fuzzy-based MCDM analysis, factors that should be considered first in selecting a refrigerant system have been successfully determined.

This study presents an innovative approach to addressing the complicated problem of refrigerant selection in cooling systems. This study introduces the interval type-2 trapezoidal fuzzy AHP for evaluating and ranking these criteria and factors. Previous research has emphasized the significance of considering various criteria and characteristics during selection. This study provides a more accurate representation of the decision-making process by employing type-2 fuzzy sets, which can effectively deal with uncertainty and model real-world scenarios. In addition, using the AHP method in conjunction with fuzzy logic is a novel combination that provides a systematic and exhaustive evaluation of refrigerant selection criteria. The results of this study not only list the factors that influence the selection of a sustainable refrigerant but also emphasize the importance of energy efficiency in this decision-making process. This research contributes to the field by introducing a novel methodology that improves the comprehension and application of sustainable refrigerant selection in cooling systems.

Section 2 presents the adopted methodology in detail. Section 3 includes the application for the refrigerant selection problem. While discussing the study's findings in Section 4 in Section 5, the study concludes with an evaluation of the results.

2. THE PROPOSED METHODOLOGY

MCDM approaches are valuable for handling comparison problems with diverse measurement units [24]. They enable the evaluation of qualitative and quantitative factors simultaneously, aiding in real-life problem-solving [25]. MCDM-based methodologies are widely used in different areas [26]. Concrete and abstract criteria pose challenges in decision-making, mainly when more abstract criteria exist. Fuzzy sets help represent data accurately and handle uncertainties and ambiguities [25].

The utilization of MCDM approaches in decision-making offers various benefits. Firstly, MCDM enables a structured and systematic evaluation and comparison of options based on multiple criteria. This approach provides a comprehensive framework for considering various factors and facilitates a thorough analysis of available alternatives. Secondly, MCDM allows for the explicit consideration and weighing of the relative importance of criteria. Decision makers can assign weights to each criterion, ensuring the final decision reflects their priorities and values. Thirdly, MCDM approaches provide a clear and transparent decision rationale, fostering stakeholder support and consensus. The systematic nature of MCDM allows decision-makers to justify their choices based on a well-defined evaluation process.

Furthermore, MCDM facilitates the identification and evaluation of trade-offs between different criteria. In situations where it is impossible to optimize all criteria simultaneously, MCDM assists in understanding the compromises and trade-offs associated with other alternatives. Lastly, MCDM approaches enable the integration and synthesizing information from multiple sources, which is particularly beneficial in complex decision-making situations. By considering diverse perspectives and combining information from various stakeholders, MCDM enhances the quality and effectiveness of the decision-making process. Fuzzy MCDM methods utilize fuzzy logic to handle uncertain or imprecise information [27]. They are beneficial when evaluating multiple options with conflicting criteria and uncertain or inaccurate information. Fuzzy sets and membership functions allow flexible representation of criteria uncertainty and subjectivity. They are valuable in decision-making where classical methods fall short [28].

Fuzzy logic, suggested by Zadeh [29, 30] deals with approximate reasoning, representing uncertainty and fuzziness in real-world situations flexibly [31, 32]. It utilizes fuzzy sets with membership degrees from 0 to 1 [33]. Fuzzy logic finds applications in control systems, pattern recognition, and natural language processing, effectively handling uncertain or imprecise information. Fuzzy set theory quantifies linguistic variables to compare alternatives. Type-2 fuzzy sets take more uncertainty and are suitable for decision-making with subjective judgments [34]. They provide a more realistic conversion of information from decision-makers into numerical values [35]. Type-2 fuzzy sets offer more flexibility and expressiveness than type-1 fuzzy sets [36], thus enhancing the decision-making process in several ways. Firstly, type-2 fuzzy sets allow for the modeling of higher levels of uncertainty by accommodating varying degrees of fuzziness within the membership function [37]. This capability is particularly relevant in complex decision-making scenarios, such as refrigerant selection, where multiple factors and criteria may exhibit different levels of uncertainty. Secondly, type-2 fuzzy sets represent uncertainty in the membership function and the uncertainty bounds associated with the membership grades [38]. This additional layer of uncertainty modeling provides decision-makers with more nuanced information about each criterion's assessment's reliability and confidence level, contributing to a more robust decision-making process.

Furthermore, type-2 fuzzy sets offer flexibility in handling conflicting and ambiguous information, which is common in real-world decision-making contexts [39]. Type-2 fuzzy sets are used in this study based on their ability to address these specific challenges inherent in refrigerant selection [40]. Adopting type-2 fuzzy sets in this study facilitated a more comprehensive analysis of refrigerant selection criteria, enhancing the decision-making process compared to traditional type-1 fuzzy sets [41].

AHP is used to model MCDM problems with tangible and intangible criteria in a hierarchical structure [42] and developed by Saaty [43]. It calculates criteria weights through pairwise comparisons based on expert judgments. AHP is chosen due to its ability to handle qualitative and quantitative criteria, ensure consistency of judgments, and create a hierarchical structure. For the sustainable refrigerant selection problem, AHP is suitable because of its hierarchical structure [44] and linguistic evaluation of decision-makers. Type-2 fuzzy AHP is a promising approach that addresses high uncertainty from experts' subjective assessment of membership degrees. MCDM approaches, AHP based on type-2 fuzzy sets, offer valuable tools to improve decision-making in complex situations, enhancing the quality and effectiveness of the process [45].

The method adopted to solve the refrigerant selection problem in the paper is expressed in detail in the following sub-sections.

2.1. Interval type-2 fuzzy sets

The definitions of type-2 fuzzy sets and interval type-2 trapezoidal fuzzy sets are introduced in this sub-section [46–48]:

Definition 1. A type-2 fuzzy set $\tilde{\tilde{A}}$ is expressed with a type-2 membership function $\mu_{\tilde{\tilde{A}}}$ in the universe of discourse X, as shown:

$$\tilde{\tilde{A}} = \{((x,u), \mu_{\tilde{\tilde{A}}}(x,u)) | \forall x \in X, \forall u \in J_X \subseteq [0,1], 0 \le \mu_{\tilde{\tilde{A}}}(x,u) \le 1\} \quad (1)$$

Where J_x denotes an interval in [0, 1]. Furthermore, the type-2 fuzzy set $\tilde{\tilde{A}}$ can be presented:

$$\tilde{\tilde{A}} = \int_{x\in X} \int_{u\in J_X} \mu_{\tilde{\tilde{A}}}(x,u) / (x,u) \quad (2)$$

where $J_x \subseteq [0,1]$ and ∫∫ show union over all admissible x and u.

Definition 2. $\tilde{\tilde{A}}$ is a type-2 fuzzy set and is presented by the type-2 membership function $\mu_{\tilde{\tilde{A}}}$ in the universe of discourse X. If all $\mu_{\tilde{\tilde{A}}}(x,u) = 1$, then $\tilde{\tilde{A}}$ is named an interval type-2 fuzzy set. An interval type-2 fuzzy set $\tilde{\tilde{A}}$ can be accepted as a specific case of a type-2 fuzzy set, presented as:

$$\tilde{\tilde{A}} = \int_{x\in X} \int_{u\in J_X} 1/(x,u) \quad (3)$$

where $J_x \subseteq [0,1]$

Definition 3. The upper and lower membership functions of interval type-2 fuzzy sets are defined as type-1 membership functions, accordingly. This study presents an approach for using interval type-2 fuzzy sets for fuzzy MCDM problems. Interval type-2 fuzzy sets are specialized using reference points and the heights of the upper and lower membership functions. Figure 2 denotes a trapezoidal interval type-2 fuzzy set $\tilde{\tilde{A}}_i = (\tilde{A}_i^U, \tilde{A}_i^L) = \begin{pmatrix} (a_{i1}^U, a_{i2}^U, a_{i3}^U, a_{i4}^U; H_1(\tilde{A}_i^U), H_2(\tilde{A}_i^U)), \\ (a_{i1}^L, a_{i2}^L, a_{i3}^L, a_{i4}^L; H_1(\tilde{A}_i^L), H_2(\tilde{A}_i^L)) \end{pmatrix}$ [47], where $\tilde{A}_i^U$ and $\tilde{A}_i^L$ are type-1 fuzzy sets, $a_{i1}^U, a_{i2}^U, a_{i3}^U, a_{i4}^U, a_{i1}^L, a_{i2}^L, a_{i3}^L$ and a_{i4}^L are the reference points of the interval type-2 fuzzy $\tilde{\tilde{A}}_i$; $H_j(\tilde{A}_i^U)$ presents the membership value of the element $a_{i(j+1)}^U$ in the upper trapezoidal membership function $\tilde{A}_i^U$; $1 \le j \le 2$, $H_j(\tilde{A}_i^L)$ presents the membership value of the element $a_{i(j+1)}^U$ in the lower trapezoidal membership function $\tilde{A}_i^L$; $1 \le j \le 2$, $H_j(\tilde{A}_i^L)$

$H_1(\tilde{A}_i^U) \in [0,1], H_2(\tilde{A}_i^U) \in [0,1], H_1(\tilde{A}_i^L) \in [0,1], H_2(\tilde{A}_i^L) \in [0,1]$ and $1 \le i \le n$.

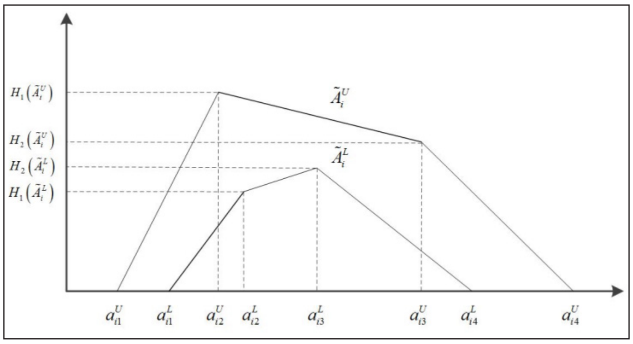

Figure 2. The membership functions of an interval type-2 fuzzy set.

Definition 4. The following equations describe the addition operation between trapezoidal interval type-2 fuzzy sets:

$$\tilde{\tilde{A}}_1 = (\tilde{A}_1^U, \tilde{A}_1^L) = \begin{pmatrix} (a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)), \\ (a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)) \end{pmatrix} \quad (4)$$

$$\tilde{\tilde{A}}_2 = (\tilde{A}_2^U, \tilde{A}_2^L) = \begin{pmatrix} (a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1(\tilde{A}_2^U), H_2(\tilde{A}_2^U)), \\ (a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1(\tilde{A}_2^L), H_2(\tilde{A}_2^L)) \end{pmatrix} \quad (5)$$

$$\tilde{\tilde{A}}_1 \oplus \tilde{\tilde{A}}_2 = (\tilde{A}_1^U, \tilde{A}_1^L) \oplus (\tilde{A}_2^U, \tilde{A}_2^L) = \begin{pmatrix} \begin{pmatrix} a_{11}^U + a_{21}^U, a_{12}^U + a_{22}^U, a_{13}^U + a_{23}^U, a_{14}^U + a_{24}^U; \\ min(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)), min(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)) \end{pmatrix}, \\ \begin{pmatrix} a_{11}^L + a_{21}^L, a_{12}^L + a_{22}^L, a_{13}^L + a_{23}^L, a_{14}^L + a_{24}^L; \\ min(H_1(\tilde{A}_1^L), H_1(\tilde{A}_2^L)), min(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)) \end{pmatrix} \end{pmatrix} \quad (6)$$

Definition 5. The following equations describe the subtraction operation between trapezoidal interval type-2 fuzzy sets:

$$\tilde{\tilde{A}}_1 = (\tilde{A}_1^U, \tilde{A}_1^L) = \begin{pmatrix} (a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)), \\ (a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)) \end{pmatrix} \quad (7)$$

$$\tilde{\tilde{A}}_2 = (\tilde{A}_2^U, \tilde{A}_2^L) = \begin{pmatrix} (a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1(\tilde{A}_2^U), H_2(\tilde{A}_2^U)), \\ (a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1(\tilde{A}_2^L), H_2(\tilde{A}_2^L)) \end{pmatrix} \quad (8)$$

$$\tilde{\tilde{A}}_1 \ominus \tilde{\tilde{A}}_2 = (\tilde{A}_1^U, \tilde{A}_1^L) \ominus (\tilde{A}_2^U, \tilde{A}_2^L) = \begin{pmatrix} \begin{pmatrix} a_{11}^U - a_{21}^U, a_{12}^U - a_{22}^U, a_{13}^U - a_{23}^U, a_{14}^U - a_{24}^U; \\ min(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)), min(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)) \end{pmatrix}, \\ \begin{pmatrix} a_{11}^L - a_{21}^L, a_{12}^L - a_{22}^L, a_{13}^L - a_{23}^L, a_{14}^L - a_{24}^L; \\ min(H_1(\tilde{A}_1^L), H_1(\tilde{A}_2^L)), min(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)) \end{pmatrix} \end{pmatrix} \quad (9)$$

Definition 6. The following equations describe the multiplication operation between trapezoidal interval type-2 fuzzy sets.:

$$\tilde{\tilde{A}}_1 = (\tilde{A}_1^U, \tilde{A}_1^L) = \begin{pmatrix} (a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)), \\ (a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)) \end{pmatrix} \quad (10)$$

$$\tilde{\tilde{A}}_2 = (\tilde{A}_2^U, \tilde{A}_2^L) = \begin{pmatrix} (a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1(\tilde{A}_2^U), H_2(\tilde{A}_2^U)), \\ (a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1(\tilde{A}_2^L), H_2(\tilde{A}_2^L)) \end{pmatrix} \quad (11)$$

$$\tilde{\tilde{A}}_1 \otimes \tilde{\tilde{A}}_2 = (\tilde{A}_1^U, \tilde{A}_1^L) \otimes (\tilde{A}_2^U, \tilde{A}_2^L) = \begin{pmatrix} \begin{pmatrix} a_{11}^U \times a_{21}^U, a_{12}^U \times a_{22}^U, a_{13}^U \times a_{23}^U, a_{14}^U \times a_{24}^U; \\ min(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)), min(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)) \end{pmatrix}, \\ \begin{pmatrix} a_{11}^L \times a_{21}^L, a_{12}^L \times a_{22}^L, a_{13}^L \times a_{23}^L, a_{14}^L \times a_{24}^L; \\ min(H_1(\tilde{A}_1^L), H_1(\tilde{A}_2^L)), min(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)) \end{pmatrix} \end{pmatrix} \quad (12)$$

Definition 7. Some basic arithmetic operations for trapezoidal interval type-2 fuzzy numbers are given:

$$\tilde{\tilde{A}}_1 = (\tilde{A}_1^U, \tilde{A}_1^L) = \begin{pmatrix} (a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)), \\ (a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)) \end{pmatrix} \quad (13)$$

$$k\tilde{\tilde{A}}_1 = \begin{pmatrix} (k \times a_{11}^U, k \times a_{12}^U, k \times a_{13}^U, k \times a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)), \\ (k \times a_{11}^L, k \times a_{12}^L, k \times a_{13}^L, k \times a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)) \end{pmatrix} \quad (14)$$

$$\frac{\tilde{\tilde{A}}_1}{k} = \begin{pmatrix} (\frac{1}{k} \times a_{11}^U, \frac{1}{k} \times a_{12}^U, \frac{1}{k} \times a_{13}^U, \frac{1}{k} \times a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)), \\ (\frac{1}{k} \times a_{11}^L, \frac{1}{k} \times a_{12}^L, \frac{1}{k} \times a_{13}^L, \frac{1}{k} \times a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)) \end{pmatrix} \quad (15)$$

Definition 8. The following is a definition of the trapezoidal interval type-2 fuzzy set's ranking value:

$$Rank(\tilde{\tilde{A}}_i) = M_1(\tilde{A}_i^U) + M_1(\tilde{A}_i^L) + M_2(\tilde{A}_i^U) + M_2(\tilde{A}_i^L) + M_3(\tilde{A}_i^U) + M_3(\tilde{A}_i^L) - \frac{1}{4}\left(S_1(\tilde{A}_i^U) + S_1(\tilde{A}_i^L) + S_2(\tilde{A}_i^U) + S_2(\tilde{A}_i^L) + S_3(\tilde{A}_i^U) + S_3(\tilde{A}_i^L) + S_4(\tilde{A}_i^U) + S_4(\tilde{A}_i^L)\right) + H_1(\tilde{A}_i^U) + H_1(\tilde{A}_i^L) + H_2(\tilde{A}_i^U) + H_2(\tilde{A}_i^L) \quad (16)$$

where $M_p(\tilde{A}_i^j)$ shows the average of the factors a_{ip}^j and $a_{i(p+1)}^j$, $M_p(\tilde{A}_i^j) = \left(a_{ip}^j + a_{i(p+1)}^j\right)/2, 1 \le p \le 3$ shows the standard deviation of the factors a_{iq}^j and $a_{i(q+1)}^j$, $S_q(\tilde{A}_i^j) = \sqrt{\frac{1}{2}\sum_{k=q}^{q+1}\left(a_{ik}^j - \frac{1}{2}\sum_{k=q}^{q+1} a_{ik}^j\right)^2}$, $1 \le q \le 3$, $S_4(\tilde{A}_i^j)$ shows the standard deviation of the factors $a_{i1}^j, a_{i2}^j, a_{i3}^j, a_{i4}^j$, $S_4(\tilde{A}_i^j) = \sqrt{\frac{1}{4}\sum_{k=1}^{4}\left(a_{ik}^j - \frac{1}{4}\sum_{k=1}^{4} a_{ik}^j\right)^2}$ $H_p(\tilde{A}_i^j)$ shows the membership value of the factor $a_{i(p+1)}^j$ in the trapezoidal membership function $\tilde{A}_i^j$, $1 \le p \le 3$, $j \in \{U, L\}$, and $1 \le i \le n$.

2.2. Trapezoidal Interval Type -2 fuzzy AHP

AHP is an MCDM method developed by Saaty [49, 50]. *The AHP method, widely recognized for determining criteria weights, is commonly employed to address complex problems involving multiple criteria [51]. AHP is adaptable, involves no complicated math, and utilizes a hierarchical structure to enhance focus and transparency in decision-making processes [52].* AHP is used. Triangular fuzzy numbers are employed in Laarhoven and Pedrycz's [53] hybridization of AHP with fuzzy logic to provide a method for usage in uncertain scenarios. The fuzzy comparison rates with the expanding

Table 2. Linguistic expressions

Linguistic Terms		Fuzzy Numbers											
Weak	**AW**	0.11	0.1	0.1	0.1	1	1	0.1	0.1	0.1	0.1	0.9	0.9
Very Veak	**VW**	0.11	0.1	0.2	0.2	1	1	0.1	0.1	0.2	0.2	0.9	0.9
Fairly Weak	**FW**	0.14	0.2	0.3	0.3	1	1	0.1	0.2	0.2	0.3	0.9	0.9
Slightly Weak	**SW**	0.2	0.3	0.5	1	1	1	0.2	0.3	0.5	0.9	0.9	0.9
Equal	**E**	1	1	1	1	1	1	1	1	1	1	0.9	0.9
Slightly Strong	**SS**	1	2	4	5	1	1	1.1	2.1	3.9	4.9	0.9	0.9
Fairly Strong	**FS**	3	4	6	7	1	1	3.1	4.1	5.9	6.9	0.9	0.9
Very Strong	**VS**	5	6	8	9	1	1	5.1	6.1	7.9	8.9	0.9	0.9
Strong	**AS**	7	8	9	9	1	1	7.1	8.1	8.9	8.9	0.9	0.9

approach were put forth by Buckley [54]. In his suggested method, the geometric mean method obtains fuzzy weights and performance scores. To more accurately depict the uncertainties in getting the criteria weights, interval type-2 fuzzy AHP—which also incorporates fuzzy membership functions—is employed in this study.

The interval type-2 trapezoidal fuzzy AHP method offers several advantages in accuracy, reliability, and computational efficiency compared to other MCDM methods, especially in complex decision-making scenarios such as sustainable refrigerant selection. First, the interval type-2 trapezoidal fuzzy AHP method provides a robust framework for capturing and managing the uncertainty and imprecision inherent in decision-making processes [55]. By allowing decision-makers to model varying degrees of uncertainty in criteria evaluations, this method provides a more accurate representation of real-world decision contexts than methods that rely solely on crisp values or type-1 fuzzy sets. Second, the interval type-2 trapezoidal fuzzy AHP method improves the reliability of the decision-making process by incorporating multiple sources of uncertainty and ambiguity into the analysis. By explicitly modeling uncertainty boundaries and considering different scenarios within the interval type-2 fuzzy framework, this method provides decision-makers with a more comprehensive understanding of potential outcomes and their associated risks. Although the interval type-2 trapezoidal fuzzy AHP method involves additional computational complexity compared to some traditional decision-making methods, advances in computational techniques and algorithms have made its application possible and efficient. In addition, the interval type-2 trapezoidal fuzzy AHP method is adaptable to specific decision contexts and problem structures, allowing efficient and scalable application in practical applications. In the context of this study, the Buckley AHP method is created using interval type-2 trapezoidal fuzzy sets. The proposed interval type-2 trapezoidal fuzzy AHP method is composed of the following steps:

Step 1. A decision hierarchy of main and sub-criteria is constructed.

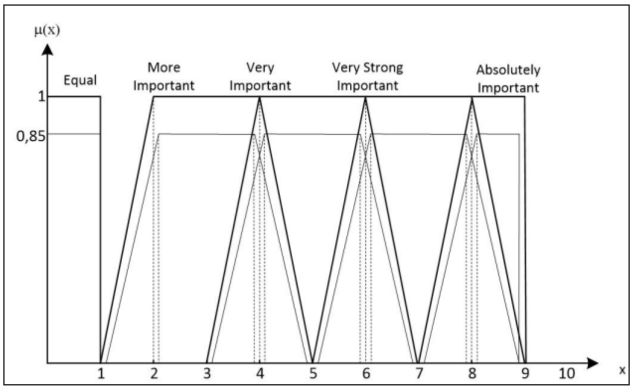

Figure 3. The membership functions of interval type-2 trapezoidal fuzzy numbers.

Step 2. It is decided on what scale will be used to evaluate the criterion. Table 2 lists the scale used in this study to transform linguistic expressions into interval type-2 trapezoidal fuzzy sets.

Figure 3 illustrates the scale's membership functions employed in this paper to guide decision-making.

Step 3. For main criteria and sub-criteria for each main criterion, pairwise comparison matrices are created in the hierarchy. The Equation 17 is a fuzzy pairwise comparison matrix:

$$\tilde{\tilde{A}} = \begin{bmatrix} 1 & \tilde{\tilde{a}}12 & \dots & \dots. & \tilde{\tilde{a}}1m \\ \tilde{\tilde{a}}21 & 1 & \dots & \dots & \tilde{\tilde{a}}2m \\ \vdots & \vdots & \dots & \dots & \vdots \\ \vdots & \vdots & \dots & \dots & \vdots \\ \tilde{\tilde{a}}1n & \tilde{\tilde{a}}2n & \dots & \dots & 1 \end{bmatrix} \quad (17)$$

$$\tilde{\tilde{a}}ij = \frac{1}{\tilde{\tilde{a}}ji} \quad (18)$$

e.g., $\tilde{\tilde{a}}31 = \frac{1}{\tilde{\tilde{a}}13}$

$$\tilde{\tilde{a}} = ((a_{11}^{U}; a_{12}^{U}; a_{13}^{U}; a_{14}^{U}; H_1(a^{U}); H2(a^{U}), \\ (a_{11}^{L}; a_{12}^{L}; a_{13}^{L}; a_{14}^{L}; H_1(a^{L}); H2(a^{L}) \quad (19)$$

Therefore,

$$\frac{1}{\tilde{\tilde{a}}} = ((\frac{1}{a_{14}^U}; \frac{1}{a_{13}^U}; \frac{1}{a_{12}^U}; \frac{1}{a_{11}^U}; H_1(a_{12}^U); H2(a_{13}^U), (\frac{1}{a_{14}^L}; \frac{1}{a_{13}^L}; \frac{1}{a_{12}^L}; \frac{1}{a_{11}^L}; H_1(a_{12}^L); H2(a_{13}^L)) \quad (20)$$

Step 4. The defuzzification process is conducted to calculate consistency indexes. The following equations determine consistency ratio (CR) [56]. The pairwise comparison matrices are consistent when the CR is less than 0.1.

$$CI = \frac{\lambda_{max}}{n-1} \quad (21)$$

$$CR = \frac{CI}{RI} \quad (22)$$

The random index (RI) varies randomly about the number of criteria, where “n” is the number of criteria. Consistency Index (CI) is determined based on the table proposed by Saaty [49].

Step 5. Geometric means of all criteria are calculated:

$$\tilde{\tilde{r}}i = [\tilde{\tilde{a}}_{i1} \otimes \tilde{\tilde{a}}_{i2} \otimes \ldots \otimes \tilde{\tilde{a}}_{im}]^{1/n} \quad (23)$$

$$(\tilde{\tilde{a}}_{ij})^{1/n} = \begin{pmatrix} (\tilde{\tilde{a}}_{i1}^U)^{1/n}, (\tilde{\tilde{a}}_{i2}^U)^{1/n}, (\tilde{\tilde{a}}_{i3}^U)^{1/n}, (\tilde{\tilde{a}}_{i4}^U)^{1/n}, H_1(a_{i2}^U), H_2(a_{i3}^U) \\ (\tilde{\tilde{a}}_{i1}^L)^{1/n}, (\tilde{\tilde{a}}_{i2}^L)^{1/n}, (\tilde{\tilde{a}}_{i3}^L)^{1/n}, (\tilde{\tilde{a}}_{i4}^L)^{1/n}, H_1(a_{i2}^L), H_2(a_{i3}^L) \end{pmatrix} \quad (24)$$

Step 6. The weights are computed via normalization as follows:

$$wi = \tilde{\tilde{r}}i = [\tilde{\tilde{r}}1 \oplus \tilde{\tilde{r}}2 \oplus \ldots \oplus \tilde{\tilde{r}}n]^{-1} \quad (25)$$

Step 7. Finally, the fuzzy numbers are defuzzified using Eq. (26) to identify the degree of importance of each criterion**.**

$$w_i' = \frac{1}{2}\left(\frac{1}{2}\sum_{i=1}^{4} (a_i^L + a_i^L)\right) \otimes \frac{1}{4}\left(\sum_{i=1}^{2} \left(H_i(A^L) + H_i(A^U)\right)\right) \quad (26)$$

3. APPLICATION

Applications for air conditioning and refrigeration have become more crucial in recent years due to global warming and high energy consumption. The significance of refrigerant selection in refrigeration systems is even more apparent when considering that cooling costs more than heating. Incorrect material choice and improper application result in issues that are difficult to resolve after the system is operational and impose significant financial expenses on the user. In this situation, it is crucial to identify the criteria that affect the choice of the best refrigerant and to evaluate their significance methodically. This study aims to identify the requirements that should be considered for refrigeration and the most essential criteria in the evaluation process. For this aim, AHP, a well-known MCDM technique, is used by consulting experts in an interval type-2 trapezoidal fuzzy environment.

Table 2 indicates expert proficiencies as the decision makers in refrigerant selection. The criteria are determined and weighted using expert opinions and available literature about the problem. When selecting experts, their skills and expertise are considered in this field. In choosing the experts to be consulted for this study on sustainable refrigerant selection, several key aspects were crucial to ensure the credibility and relevance of their contributions. First, priority is given to experts with deep expertise in refrigerant selection, sustainable practices, environmental management, and multi-criteria decision making methodologies. Their reputation, experience, and publication record are thoroughly evaluated to ensure they have a track record of high-quality research and contributions to the field. It is critical to select experts who are available and accessible for consultation and have strong communication skills to facilitate fruitful collaboration. Careful consideration is also given to identifying and managing potential conflicts of interest to protect the integrity of the study. By carefully considering these factors, a panel of experts is assembled, ready to provide valuable insight and expertise and to validate the findings and conclusions of the study with the expert group. E-1, E-2, E-3, E-4, E-5, E-6, and E-7 are the abbreviations for seven decision-makers with a deep knowledge of the HVAC sector. Because each expert has a different experience level, as shown in Table 3, their weights (reputations) also differ. Although all experts are mechanical engineers, five have academic careers, and the remaining two work as engineers in the HVAC sector.

3.1. Evaluation criteria

Based on the literature review and expert opinions, a two-level criteria framework is created to prioritize the factors related to the refrigerant selection problem.

Table 3. Expert proficiencies as a decision-maker

Experts	Career	Title	Experience	Field	Reputation (Expert Weight)
E-1	Academician	Asst. Prof.	7	Mechanical Engineering	0.2
E-2	Academician	Res. Asst.	5	Mechanical Engineering	0.1
E-3	Academician	Prof. Dr.	15+	Mechanical Engineering	0.1
E-4	Engineer	HVAC specialist	3	Mechanical Engineering	0.1
E-5	Academician	Res. Asst.	7	Mechanical Engineering	0.1
E-6	Academician	Prof. Dr.	20+	Mechanical Engineering	0.2
E-7	Engineer	HVAC specialist	20+	Mechanical Engineering	0.2

Table 4. Main and sub-criteria

Main Criteria	Sub Criteria	References
C1. Environmental	C11. Ozone depletion potential	[2], [3], [6], [10]–[12], [14]–[19]
	C12. Global warming potential	[2]–[4], [6], [10]–[12], [14]–[19]
	C13. Secondary environmental impacts	[2]
	C14. Flammability	[2], [3], [6], [10]–[12], [14], [15], [17]–[19]
	C15.Toxicity	[2], [3], [10]–[12], [14], [15], [17], [19]
C2. Thermodynamic	C21. Latent heat of vaporization	[10]–[12], [15], [16], [19]
	C22. Thermal conductivity	[3], [11], [12], [16]
	C23. Vapor pressure	[6], [10]–[12], [14], [15]
	C24. Liquid density	[3], [6], [10]–[12], [15], [16]
	C25. Liquid viscosity	[3], [10]–[12], [16]
	C26. Normal boiling point	[3], [4], [6], [14], [16], [17], [19]
C3. Sustainability	C31. Operation life	[2], [6], [16], [17], [19]
	C32. Recyclable content	[2]
	C33. Material use	[2]
	C34.Energy efficiency	Expert view
	C35.Refrigerant cost	[2], [11], [12]
	C36.Materials compatibility	[2]

Table 5. Pairwise comparison matrices for main criteria

Expert		**1**			**2**			**3**			**4**	
Criteria	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
C1. Environmental	E	E	FW	E	SS	VS	E	VW	VS	E	AS	FS
C2. Thermodynamic	E	E	SW	SW	E	FS	VS	E	AS	AW	E	SW
C3. Sustainability	FS	SS	E	VW	FW	E	VW	AW	E	FW	SS	E
Expert		**5**			**6**			**7**				
Criteria	C1	C2	C3	C1	C2	C3	C1	C2	C3			
C1. Environmental	E	VW	SW	E	SS	SS	E	SW	AW			
C2. Thermodynamic	VS	E	E	SW	E	E	VS	E	VW			
C3. Sustainability	SS	E	E	SW	E	E	FS	VS	E			

Three main criteria—environmental, thermodynamic, and sustainable make up the first level. Table 4 presents the main and sub-criteria for refrigerant selection.

Table 6. CR values for main criteria comparisons

Expert	1	2	3	4	5	6	7
CR	0.03	0.091	0.084	0.03	0.084	0	0.084

3.2 Determining the criteria weights for each level of the hierarchy

Seven experts are consulted, as explained before, and are required for criteria evaluation for each level through a questionnaire to determine the weights of the criteria. First, a pairwise comparison matrix is constructed for the main criteria by each expert based on linguistic variables in Table 2. Table 5 shows the matrices for the main criteria created by experts.

The consistency of the experts' opinions is examined; if the pairwise comparisons are inconsistent, the experts are asked to reassess. In response to inconsistencies identified by the CR, the revision process involves reviewing expert judgments and seeking consensus among experts. Re-evaluation of the relevance of the criteria further resolves inconsistencies and ensures robust decision outcomes. The weight calculation phase is initiated when the CR is less than 0.1 [57], indicating that the relevant matrix is consistent. The CR values for the pairwise comparisons of the main criteria for each expert are shown in Table 6. All matrices are determined to be consistent, as shown in Table 6.

Table 7. Main criteria weights

Criteria/Expert	1	2	3	4	5	6	7
C1. Environmental	0.156	0.627	0.198	0.734	0.110	0.584	0.076
C2. Thermodynamic	0.197	0.301	0.751	0.080	0.511	0.208	0.152
C3. Sustainability	0.647	0.073	0.051	0.186	0.379	0.208	0.772

Table 8. Pairwise comparison of Expert-1 for sub-criteria of Environmental

Sub-Criteria	C11	C12	C13	C14	C15
C11. Ozone depletion potential	E	E	SS	AW	AW
C12. Global warming potential	E	E	SS	AW	AW
C13. Secondary environmental impacts	SW	SW	E	AW	AW
C14. Flammability	AS	AS	AS	E	SS
C15.Toxicity	AS	AS	AS	SW	E

Table 9. Pairwise comparison of Expert-3 for sub-criteria of Thermodynamic

Sub-Criteria	C21	C22	C23	C24	C25	C26
C21. Latent heat of vaporization	E	AW	AW	SS	E	VW
C22. Thermal conductivity	AS	E	E	AS	AS	SS
C23. Vapor pressure	AS	E	E	AS	FS	VS
C24. Liquid density	SW	AW	AW	E	E	FW
C25. Liquid viscosity	E	AW	FW	E	E	FW
C26. Normal boiling point	VS	SW	VW	FS	FS	E

Table 10. Consistency ratios for sub-criteria evaluations

Expert	1	2	3	4	5	6	7
For Sub-criteria of Environmental	0.078	0.091	0.066	0.087	0.084	0.063	0.099
For Sub-criteria of Thermodynamic	0.096	0.085	0.082	0.087	0.087	0.095	0.095
For Sub-criteria of Sustainability	0.096	0.095	0.089	0.09	0.087	0.099	0.096

The weights of the main criteria are computed by using the interval type-2 trapezoidal fuzzy AHP steps once all pairwise comparison matrices have been consistently obtained. Table 7 presents the main criteria weights based on expert opinions.

It can be noticed that Environmental (C1) is the most essential criterion for three experts (E-2, E-4, and E-6), and Thermodynamic (C2) is the most critical criterion for two experts (E-3 and E-5). Lastly, Sustainability (C3) is evaluated as the most crucial main criterion by two experts (E-1 and E-7). From this point of view, it can be said that experts have different opinions according to their knowledge and experience. Thus, making a more inclusive evaluation is possible by taking experts' opinions with other ideas.

The same experts are consulted to assess the second level of the criteria. For this reason, expert opinions are used to build pairwise comparison matrices for the sub-criteria. For instance, Table 8 displays the pairwise comparison matrix constructed using Expert-1's assessments of the sub-criteria under the Environmental main criterion. Additionally, Table 9 shows the pairwise comparison matrix constructed using Expert-3's judgments of the sub-criteria for the Thermodynamic main criterion.

The pairwise comparison matrices for the sub-criteria are first examined for consistency, and each is consistent. Table 10 displays the CR value for each matrix.

The criteria weights for the second level are computed by reapplying the interval type-2 trapezoidal fuzzy AHP steps after determining the consistency of all matrices. Table 11 lists the sub-criteria weights considering each expert.

The priority scores for each sub-criteria are determined, as shown in Figure 4, by multiplying the aggregated

Table 11. The weights of sub-criteria for each expert

Sub-Criteria/Expert	1	2	3	4	5	6	7
C11. Ozone depletion potential	0.060	0.196	0.075	0.287	0.044	0.285	0.093
C12. Global warming potential	0.060	0.379	0.322	0.360	0.081	0.176	0.086
C13. Secondary environmental impacts	0.036	0.040	0.039	0.031	0.048	0.059	0.025
C14. Flammability	0.500	0.193	0.195	0.099	0.260	0.195	0.412
C15. Toxicity	0.343	0.193	0.370	0.222	0.568	0.285	0.385
C21. Latent heat of vaporization	0.472	0.490	0.044	0.392	0.327	0.399	0.084
C22. Thermal conductivity	0.062	0.082	0.349	0.181	0.112	0.271	0.023
C23. Vapor pressure	0.201	0.109	0.373	0.215	0.169	0.121	0.149
C24. Liquid density	0.037	0.046	0.034	0.053	0.057	0.072	0.101
C25. Liquid viscosity	0.037	0.032	0.043	0.034	0.057	0.037	0.138
C26. Normal boiling point	0.190	0.242	0.156	0.124	0.278	0.100	0.506
C31. Operation life	0.098	0.220	0.229	0.202	0.283	0.225	0.267
C32. Recyclable content	0.063	0.159	0.116	0.160	0.120	0.068	0.064
C33. Material use	0.068	0.041	0.028	0.024	0.054	0.056	0.022
C34. Energy efficiency	0.362	0.470	0.508	0.484	0.409	0.249	0.427
C35. Refrigerant cost	0.165	0.047	0.051	0.067	0.072	0.342	0.100
C36. Materials compatibility	0.244	0.063	0.068	0.063	0.062	0.060	0.119

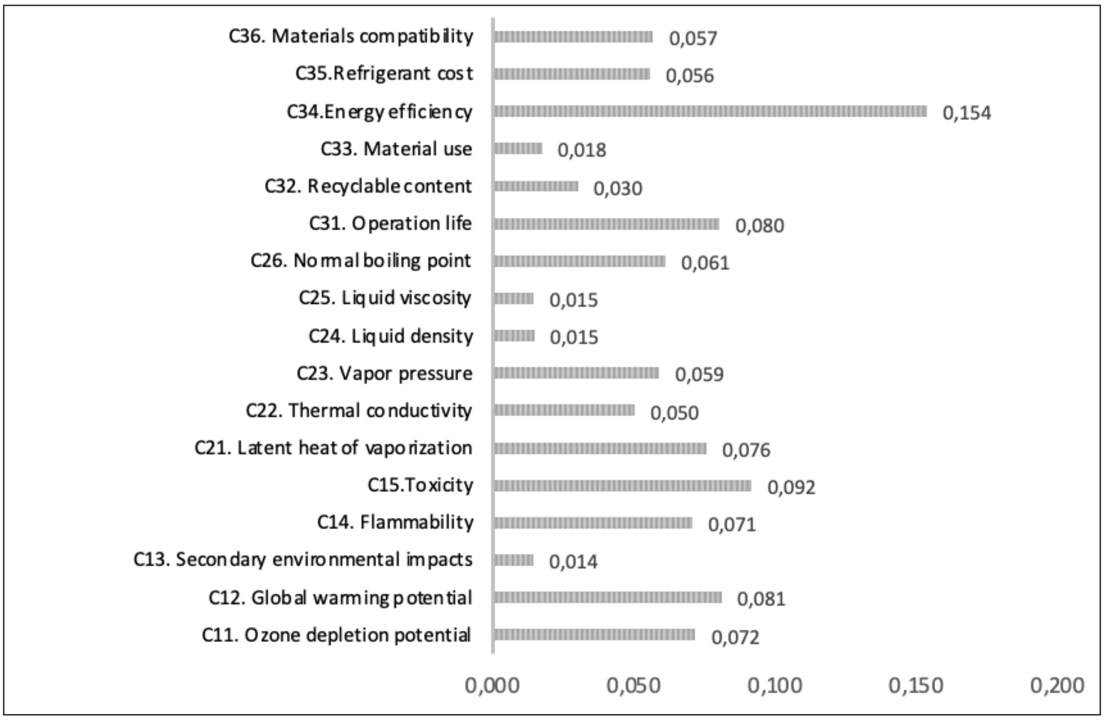

Figure 4. Sub-criteria weights.

sub-criteria weights by the corresponding main criterion weights. The criteria weights of 7 experts are compiled, considering the weights (reputations) of experts.

Energy efficiency (C34) is the most significant criterion among all sub-criteria. This outcome is expected because sustainability (C3) is the main criterion that matters the most to the two experts with the highest reputations. With final weights of 0.092 and 0.081, respectively, Toxicity (C15) and Global warming potential (C12) rank second and third. This rating illustrates that choosing a refrigerant is influenced by the Sustainability factor and the sub-criteria stated below, and decision-makers should consider this. The fourth ranking, Operation Life (C31), shows the significance of choosing a refrigerant with a

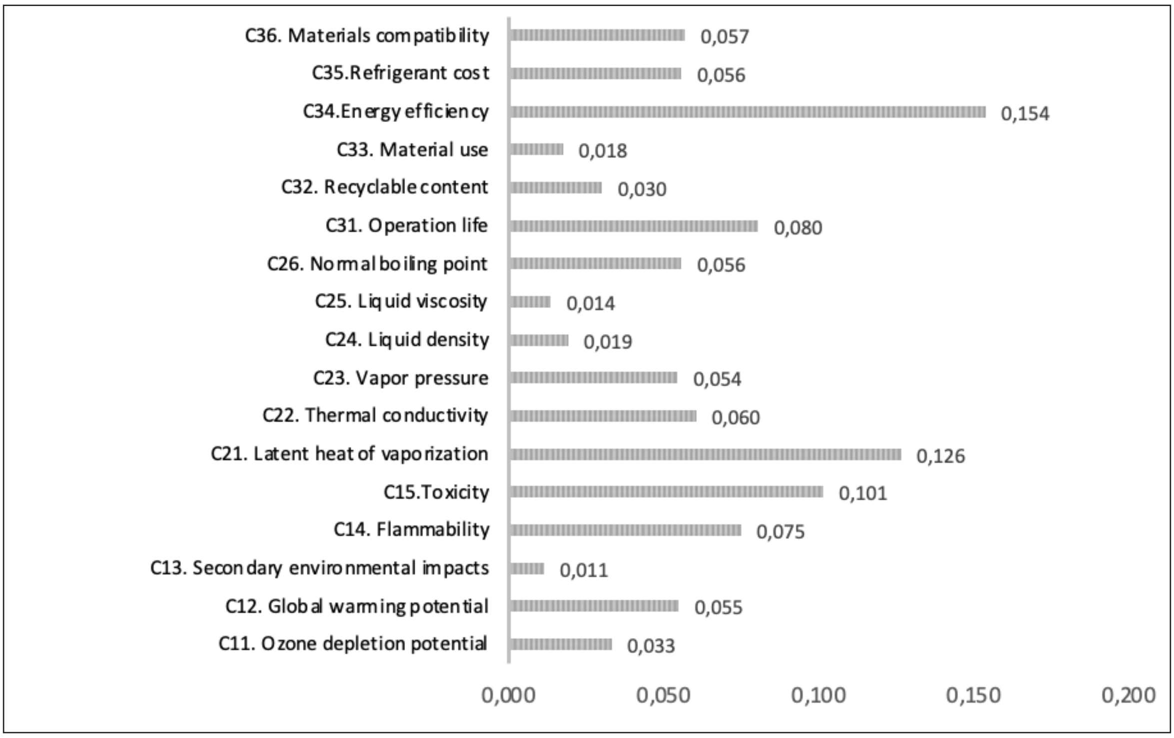

Figure 5. The weight changes of sub-criteria show that the proposed method is sensitive to small changes.

long lifetime. Secondary environmental effect (C13), one of the sub-criteria of the Environmental main criteria, is the least significant criterion. It implies that focusing on more essential criteria in the selection process would be more acceptable and that this criterion is not very important when choosing refrigerants.

3.3. Sensitivity Analysis

A sensitivity analysis is conducted to examine and evaluate the proposed methodology. In this process, the weights of the primary criteria derived from interval type-2 trapezoidal fuzzy AHP are modified between two main criteria while keeping the third constant. This involves sequentially replacing the weight of the first main criterion with those of the second and third criteria while maintaining the other constant. Subsequently, the sub-criteria weights are recalculated to assess the proposed methodology's behavior in response to weight changes. These results aid decision-makers in establishing priorities and facilitating the analysis process.

Moreover, as the weights of the main criteria change reciprocally, the overall weights of the sub-criteria also fluctuate. For instance, if we interchange the primary criteria "Environmental" and "Thermodynamic," the global weight of sub-criteria such as "Ozone depletion potential" decreases from 0.072 to 0.033. In contrast, the weight of "Latent heat of vaporization" increases from 0.076 to 0.126. The weights of sub-criteria are provided in Figure 5. The results show that the proposed method is sensitive to small changes.

4. DISCUSSION

This study initially identified criteria based on a comprehensive literature review and consultation with experts to ensure relevance to the decision-making context. Subsequently, the interval type-2 trapezoidal fuzzy AHP methodology is employed to assign weights to these criteria. Furthermore, to ensure the accuracy and validity of the results, the obtained criteria weights are verified through interviews with experts in the field. This approach ensured that the selected criteria accurately reflected the decision-making context. To reduce the impact of individual biases and limited perspectives, this study uses a variety of strategies, including diverse expert panels, rigorous validation processes, sensitivity analyses, and transparency in decision-making, ensuring that the final decision reflects a consensus-based, comprehensive assessment of all relevant factors.

As mentioned in the introduction, the energy consumption of refrigeration systems in domestic and industrial usage is approximately 20% worldwide [1]. Refrigeration and air conditioning are no longer considered luxuries because they are indispensable for food, health, and financial services but also for human comfort [58]. As a result of the ever-increasing number of refrigerators in all areas of our lives, there is a dramatic increase in energy demand and emissions, a growing contribution to global warming. Therefore, the energy efficiency of refrigerator systems is critical to postpone the global warming potential. Energy efficiency refers to the energy cost required to achieve a specific goal. The review study of McLinden et al. [2], it is indicated that the main aim is to achieve refrigeration with new refrigerants while maximizing energy efficiency by minimizing environmental impact. In the study of Poongavanam et al. [9], they selected the best refrigerant by considering thermal properties, ecological impacts, and cost. When examined their selected R430A, which is the best refrigerant according to their criteria, it is seen that the thermodynamic properties of the refrigerant, i.e., its efficiency, are prioritized over environmental impacts such as GWP and ODP in the selection of refrigerant. This situation in Poongavanam et al. [9] study supports energy efficiency as the most influential criterion identified in the present study. Prabakaran et al. [10] selected the refrigerant among 14 alternatives by considering many criteria such as power construction, coefficient of performance, total environmental impacts, thermodynamic properties, cost, and lifetime. While R444B refrigerant was the best alternative regarding coefficient of performance, total environmental impacts, lifetime, and cost, R290 refrigerant was the best alternative regarding refrigerant charge and discharge pressure. While the selection of R444B refrigerant supports the results of the present study, while that of R290 refrigerant does not. The Natural Resources Defense Council (NRDC) proposed strategies for enhancing air conditioners (ACs) in India to rapidly expand the use of energy-efficient and low-GWP refrigerants [59]. As the studies above address, energy efficiency is the most valuable criterion in the selection of refrigerants. Studies on increasing the refrigerant energy efficiency of refrigerants also show the importance of energy efficiency in the selection of refrigerants, which is also emphasized in this study.

5. CONCLUSION

Refrigeration systems are crucial for home and commercial applications, including ice production, air conditioning, and air separation. Due to the wide applications of refrigeration systems in daily life, refrigerants are not a significant threat inside the system, but their leakage and discharge to the environment pose a significant threat to the environment by causing global warming and ozone depletion. On the other hand, the refrigeration system's performance is primarily based on the refrigerant performance, so developing highly efficient and environmentally friendly refrigerant is indispensable. The refrigerant choice for the refrigeration system is critical because it affects operating conditions and cycle performance. This study analyzes the refrigerant selection criteria by considering sustainability, environmental, and thermodynamics dimensions under ambiguous conditions. The interval type-2 trapezoidal fuzzy AHP approach, which allows multiple criteria to be evaluated simultaneously, solves the factors of the refrigerant selection problem. Three main criteria and 17 sub-criteria are determined in this study. The adoption of interval type-2 trapezoidal fuzzy AHP approach in the refrigerant selection is presented as a methodology to reveal the more suitable criteria. In this way, MCDM analysis is then carried out. The most significant criterion in the proposed multi-criteria analysis is "energy efficiency," the least considerable criterion is "secondary environmental impact." Although "vapor pressure," "latent heat of vaporization," and "material compatibility" are determined as other significant criteria, energy efficiency is almost twice as substantial as the second-most important criterion. Refrigerant and refrigeration systems developers can use the proposed methodology to improve their system performance by considering determined sub-criteria such as energy efficiency, GWP, vapor pressure, etc.

The main contributions of this study are as follows: (1) The Refrigerant selection problem is handled as an MCDM problem; (2) The most significant refrigerant selection criteria are identified and categorized in a hierarchical structure; (3) These main criteria and their sub-criteria are evaluated under uncertain conditions, and the weight of each criterion is determined; and (4) To the best of authors' knowledge, this study presents the first decision-making model for refrigerant selection problem. These contributions demonstrate how this fuzzy decision-making model incorporates several innovative elements in method and application domains, ensuring the study has novel characteristics for the pertinent literature.

Limitations of this study include potential biases in expert opinions, the complexity of integrating interval type-2 trapezoidal fuzzy AHP into decision-making processes, and the need for further validation of results in different contexts. Future research could use larger and more diverse expert panels to address these limitations, increase transparency in the decision-making process, and conduct comparative analyses to assess the robustness of this model. Additional criteria can be added, or the fuzzy AHP methodology can be developed better to capture the uncertainties and complexities in the decision-making process.

The proposed interval type-2 trapezoidal fuzzy AHP approach can efficiently handle larger and more complex decision problems by establishing hierarchical structures. Such problems can be decomposed into smaller, more manageable sub-problems, allowing faster and more scalable solutions. This hierarchical decomposition strategy makes it possible to effectively navigate the complexities of decision-making while optimizing the use of computational resources. Future recommendations include using various MCDM methods to verify the findings or probabilistic approaches to look at the issue from a probabilistic viewpoint. Different MCDM methods can extend this framework with different fuzzy environments, and heating and refrigeration materials can be evaluated for various cases. Integrating interval type-2 trapezoidal fuzzy AHP with other decision-making tools or software provides numerous advantages. For example, it combines different methodologies, enabling the selection of the most suitable refrigerant among alternatives. Furthermore, the integration allows the creation of various scenarios to validate results while taking advantage of advanced visualization and reporting tools for advanced analysis.

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AVAILABILITY OF DATA AND MATERIAL

Not applicable

CODE AVAILABILITY

Not applicable

CONSENT TO PARTICIPATE

Not applicable

CONSENT TO PUBLISH

The author confirms that the final version of the manuscript has been reviewed, approved, and consented to for publication.

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