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Review Article

Drop-in and retrofit refrigerants as replacement possibilities of R134a in domestic/commercial refrigeration and automobile air conditioner applications

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ABSTRACT

According to the EU F-gas Regulation, the phase-out of the high global warming potential (GWP) refrigerants (with higher than 150 GWP value) had been established. The most currently existing household and commercial refrigerators and automobile air conditioners applications based on single-stage vapour compression systems operate with R134a as working fluid. The present paper aims, to review and evaluate the performance of a set of eco-friendly alternatives refrigerants to replace R134a, without change or with minor modifications in refrigeration equipment. The theoretical and experimental studies performed in this field of research were reviewed for this objective. These alternative refrigerants are some of HFCs, HFOs and HCs and their mixtures, which are expected to be an excellent candidates in many refrigeration applications. There are Many replacement possibilities had been proposed viz. drop-in replacement, retrofit refrigerant, and new systems. The results exhibited that the most suitable refrigerants as R134a drop-in substitutes are R1234yf, R152a, R450A, and R513A. The pure R1234ze and its mixtures are not suitable drop-in replacements of R134a but can be a good alternative to R134a only in new refrigeration systems. In terms of hydrocarbon refrigerants R290, R600, and R600a could replace R134a with some modifications to existing refrigeration systems to overcome the flammability issue. We should be using certain HFC and HC mixtures with the lowest TEWI index.

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INTRODUCTION

The household refrigeration (HR), commercial refrigeration (CR) and automobile air conditioner (AAC) applications have an important essential function: they transfer heat from a low temperature enclosed space into the high-temperature external surrounding [1]. The most common way to transmit heat between a source and a sink in refrigeration applications is by using single-stage vapour compression refrigeration (VCR) systems [2]. The VCR system used in the refrigeration devices, run on halogenated refrigerants as working fluid like chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) as well as hydrofluorocarbons (HFCs), [3], which are widely available, affordable and have excellent thermodynamic and thermo-physical properties. Table 1. Presents major categories of refrigerants employed in refrigeration and automobile air conditioner systems.

As Dalkilic and Wongwises [4] pointed out, the high chlorine content in the CFCs and HCFCs refrigerants is responsible for the destruction of the ozone layer in the atmosphere that protects the earth from harmful levels of UV rays. In addition to that fluorinated refrigerants are also greenhouse gases that increase the surface temperature of the Earth. The environmental effects have been covered by numerous studies, such as, [5,6].

HFCs have been proposed as a substitute for CFC and HFC refrigerants in various refrigeration applications. The effect of HFCs on climate change is quite serious compared to CO_2, because of the fluorine content in their molecules. R134a is commonly used in medium temperature refrigeration applications. Its global warming potential (GWP ≈1300), is a thousand times greater than those of CO_2 [7]. As a result, R134a is included in the greenhouse gases (GHGs) categories [8,9].

Consequently, using these refrigerants has become a global matter of concern. Otherwise, it will yield endless environmental problems. In order to lessen the environmental impacts, many nations were adopted the Montreal Protocol and called for the phasing-out of all CFCs in 2010.

According to the Montreal Protocol, the production and consumption of HCFCs were entirely restricted in developed countries by 2030, while in developing countries by 2040 [12,13]. The plan of the phase-out of CFC and HCFC refrigerants in developed (non-Article 5) and developing (Article 5) countries was illustrated in Fig. 1.

In Europe, the first ban was placed on using HFCs in an automobile air conditioner is based on Directive 2006/40/EC [15]. Then, the F-Gas Regulation [16,17] extended the GWP limits of the alternative refrigerants (with lower than 150 GWP value) of most new VCR systems. In the European Union, the schedule of the phase-out of HFCs has been established and already started since 1 January 2015 [18]. To reach this target, and fully eliminated the halogenated refrigerants, it is necessary to develop eco-friendly refrigerants to replace them [19]. The expected time plan for the phase-down of HFCs for developed nations was starting since 2019, while for developing countries being under the amendment's Kigali of the Montreal agreement, as shown in Fig. 2.

Hydrofluoroolefins (HFOs) are synthetic refrigerants that have been proposed as viable promising candidates to replace R134a in various refrigeration applications with minor modifications to the system. R1234yf and R1234ze(E) are among them that have been examined theoretically and experimentally. Hydrocarbons (HCs) and their mixtures as natural refrigerants are suitable substitutes for R134a in existing refrigeration systems. HC refrigerants returned to the forefront again due to having many desirable properties.

Table 1. Summary of different types of refrigerant and main properties[10,11]

Substance type	Abbreviation	ODP	GWP100 [year]	GWP20 [year]	Atmospheric Lifetime (years)	Instance (blowing agent for foams / refrigerant)
Saturated chloro-Fluorocarbons	CFCs	0.6-1	4750–14400	6730–14400	45–1700	R11, R12
Saturated hydro chloro-fluorocarbons	HCFCs	0.02-0.11	77–2310	273–5490	1.3–17.9	R141b, R22
Average			1502	4299	11.4	
Saturated hydro-Fluorocarbons	HFCs	-	120–14800	437–12000	1.4–270	R134a, R32
Average			2362	4582	21.7	
Unsaturated hydro-Fluorocarbons	u-HFCs	-	<1–12	-	days	R1234yf, R1234ze and R1234yz
Natural refrigerants		-	0–20		3	R600a, R717 R744

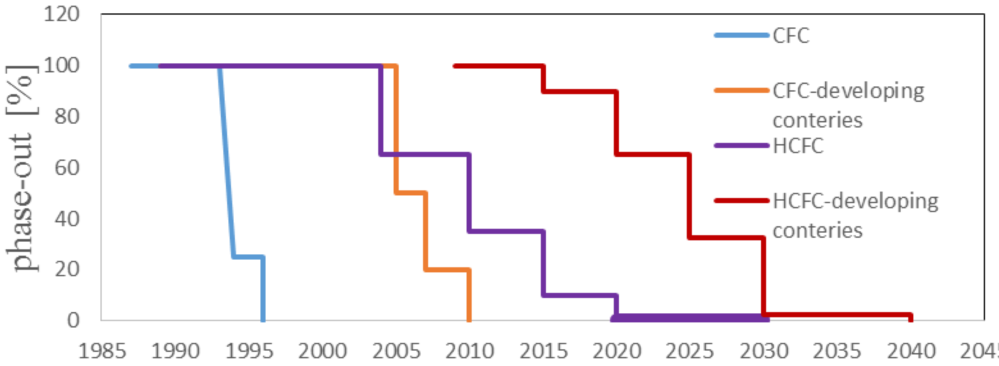

Figure 1. The schedule for non-article 5 and article 5 to phase-out the CFCs and HCFCs refrigerants [14] updated.

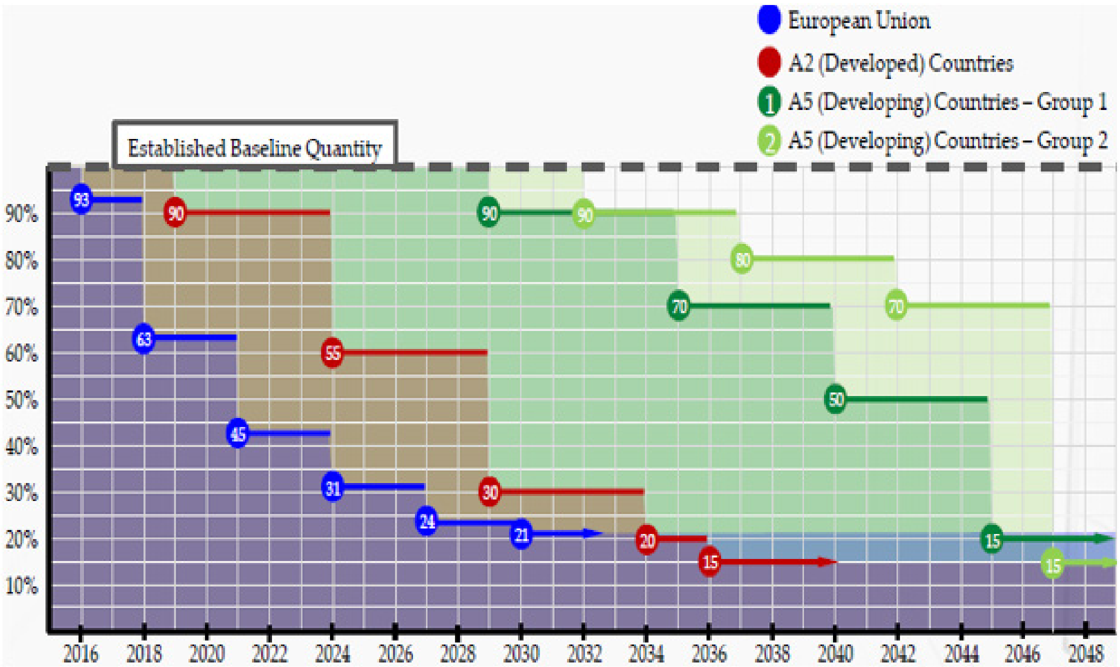

Figure 2. Expected time plan to phase-down of HFCs for developed and developing countries [20].

The flammability is the main drawback facing using the HC refrigerants as working fluids in most applications. Indeed, replacing the R134a refrigerant with HFOs and HCs and their mixtures have become a mandatory matter.

In the following reviewed literature, there are no studies that widely addressed the possibilities of replacing R134a with alternative refrigerants in HR, CR and AAC applications. In this context, three replacement possibilities were considered: drop-in replacement, retrofit refrigerants, and refrigerants used in the newly built system. As a result, this paper aims to review and evaluate the performance of various environmentally friendly refrigerants and their mixtures in terms of energy consumption, cooling capacity, refrigerant charge, COP and Total Equivalent Warming Impact (TEWI) and the possibilities of replacing the R134a in some existing VCR systems. The use of eco-friendly refrigerants and their mixtures ensures cleaner cold production by reducing direct and indirect emissions of greenhouse gases.

The paper is structured as follows: the second section reviews the refrigerants used in the VCR system and the third section presents environmental issues and presents a method for calculating TEWI. the fourth part address refrigerants replacement scenarios. results and discussion and conclusions are presented in sections 5 and 6, respectively.

Refrigerants used in VCR System

The refrigerant extracts the heat from the enclosed space to be cooled through the evaporator and then reject it to the outside by the condenser. When appropriate changes occur in the internal energy, the refrigerant may change the phase from liquid to vapour.

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In past decades, CFCs as synthetic refrigerants with excellent thermodynamic and physical properties, non-flammability, non-toxic, and obtainable at low cost has been introduced. CFC refrigerants were widely used in different refrigeration applications. The use of refrigerants with no ODP and low GWP will continue to play an essential role in the required measures of reducing greenhouse gas emissions. The high ODP of CFCs led to their replacement with HCFCs that have lower ozone depletion potential, followed by HFCs that have zero ODP.

The efforts are concentrated on identifying efficient new eco-friendly refrigerants. In HR, CR as well as AAC systems, HCs (natural refrigerants) and HFOs (synthetic refrigerants) are recommended as present and future viable solutions [21,22]. Industrial refrigerants should be either replaced or restricted to used only in applications where their replacement is economically or technically impossible. The most important principle in selecting a working liquid is system performance. A correct evaluation of the thermodynamic properties of the refrigerants is crucial. The categories of refrigerants presented in this work are illustrated in Fig. 3. According to this classification, the two main categories are pure refrigerants (pure compound) or mixed refrigerants (a mixture of two or more refrigerants).

Thermodynamic Properties of Refrigerants

Table 2. Illustrates the thermodynamic properties of some refrigerants proposed to work as an alternative to R134a. The physical, harmlessly, environmental impact, and relevant regulations are fundamental factors in the adoption of new refrigerants [24]. The refrigerant mixture should have several thermophysical properties like high thermal conductivity, low gliding temperature, low viscosity, ...etc. The rule for selecting the most suitable refrigerants for household refrigerators or automobile air conditioner systems must be based on several criteria [25]. Although alternative refrigerants are highly efficient in terms of energy and are environmentally friendly, they do not meet the other requirements in order to become viable alternatives for the refrigerants currently in use.

ENVIRONMENTAL ISSUES

The essential aim when designing refrigeration systems is their high efficiency. Nevertheless, the environmental issues for safety and practical considerations must be taken into account [18]. Three indexes commonly used to determine the effect of refrigerants on the environment are ODP, GWP, and TEWI.

Ozone Depletion Potential

Chlorine and bromine molecules are known to react with ozone, thus, have one of the most critical environmental impacts, due to destroying it the ozone layer in the stratosphere [26]. The Ozone Depleting Potential (ODP) index was created to define how much an Ozone Depleting Substances (ODSs) and its chemical compound can destroy the ozone layer relative to the effect of the equivalent mass of the trichlorofluoromethane CFC-11 molecule, which has been taken as the standard of the reference value. It has a value of 1[23]. ODP depends on the number of chlorine and bromine atoms inside the molecule and on the atmospheric lifetime of the molecule itself. The high ODP substances were successfully controlled, under the Montreal Protocol [27]. A popular group of refrigerants introduced to replace ODSs was the group of hydrofluorocarbons (HFCs) with zero ODP.

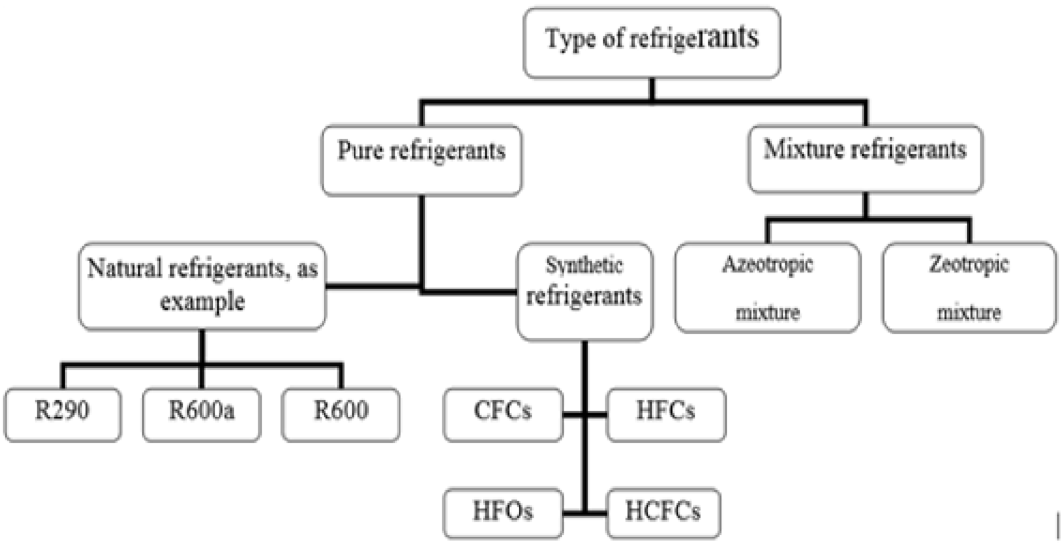

Figure 3. Types of refrigerants used in VCR system.

Table 2. Available physical properties and safety class of selected refrigerants used as substitutions of R134a [23]

ASHRAE designation of Refrigerants	Chemical formula or Composition (% by mass)	Molecular weight [$gmol^{-1}$]	Boiling point [°C]	Critical temperature [°C]	Critical pressure [MPa]	Safety class
R134a	CF_3CH_2F	102	–26.1	101.1	4.06	A1
R290	C_3H_8	44.1	–42.1	96.7	4.25	A3
R600a	C_4H_{10}/isobutane	58.12	–11.7	134.7	3.64	A3
R600	C_4H_{10}/butane	58.12	–0.5	152	3.8	A3
R1234yf	CH_2CFCF_3	114.04	–29.4	94.7	3.382	A2L
R1234ze	$CF_3CH{=}CHF$	114.04	–19	111.25	3.576	A2L
R152a	CHF_2CH_3	66.05	–24	113.3	4.76	A2
R32	CH_2F_2	52.02	–51.71	78.25	5.81	A2
R450A	R134a/R1234yf/R1234ze	75	–22	105.87	3.814	A1
R513A	R134a/R1234yf (56:44)	108.4	–27.9	97.51	3.67	A1
R436A	R290/R600a(56:44)	84	–34.3	115.9	4.17	A3
HC-12a	R290/R600a (60:40)	48.807	–34.97	113.0	4.186	A3
R430A	R152a/R600a (76:24)	64.14	–27.6	118.43	4.3	A3

Global Warming Potential (GWP)

When the world discussed global warming in the 1990s, the refrigerant gases were one of the significant problems, as some of the gases absorb the infrared radiation from the sun such as the CH_4, or CO_2 and CFCs, HCFCs and HFCs [28]. The global warming index is an indicator that measures how much energy is absorbed by a gas relative to carbon dioxide of a similar mass.

The reference value is equal to 1, and it indicates the heat absorbed by carbon dioxide [27]. The GWP of refrigerants is calculated over 20, 100, or 500-year time-horizons, with the 100-year horizon being used in general [29]. The absorption of infrared radiation, the atmospheric lifespan of the refrigerant, and the time horizon considered are factors that influence the GWP. The effects of greenhouse gas on global warming may vary depending on the time horizon [30]. The unbalanced climate due to increasing greenhouse gas emissions, fossil fuel burning, increasing the demand for heating and air conditioning, and using the different kinds of the refrigerant having a negative impact on global warming. The CO_2 atmospheric emissions have increased as a result of these factors [1]. Fig. 4 illustrates the GWP index for many refrigerants.

Total Equivalent Warming Impact (TEWI)

TEWI refers to the overall environmental impact index measure that has been developed to calculate the global warming effect of the refrigeration systems that combines the direct refrigerant emissions resulting refrigerant leakage during maintenance services, as well as, indirect emissions associated with burning the fossil fuel to generate the electric power required to operate different refrigeration equipment [31]. The TEWI index is more difficult to estimate than the GWP and the ODP ones [32,33]. For further information, to calculate the TEWI value is given by the formula below [34]:

$$TEWI = (GWP \cdot L \cdot n) + (GWP \cdot m[1 - \alpha]) + n \cdot E \cdot \beta \qquad (1)$$

REFRIGERANTS REPLACEMENT SCENARIOS

Several theoretical and experimental studies were found in the literature related to HFC, HFO, HC, and their blends as an alternative to halogen cooling in the HR, CR and AAC applications. Therefore, different refrigerant replacement possibilities of R134 were implemented viz. drop-in replacement, retrofit refrigerant, and new systems. Those attempts to use the low GWP alternative refrigerants are summarized in Fig. 5.

Replacement Scenario of Refrigerants as a Drop-in

Drop-in replacement is that case when the old refrigerant is taken out and the system charged with the alternative refrigerant and sometimes with some slight changes to the control settings [35]. This option includes the pure exchange of working fluids without any modification of the refrigeration facility and maintaining the existing lubricant oils. This replacement scenario of refrigerants was applied in the household refrigerator, mobile air conditioner, and commercial/industrial refrigeration systems.

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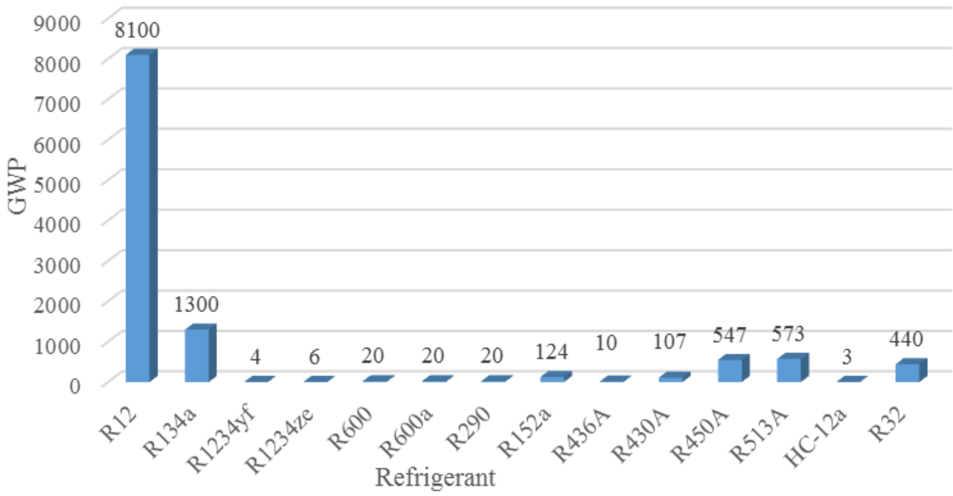

Figure 4. GWP of some selected refrigerants.

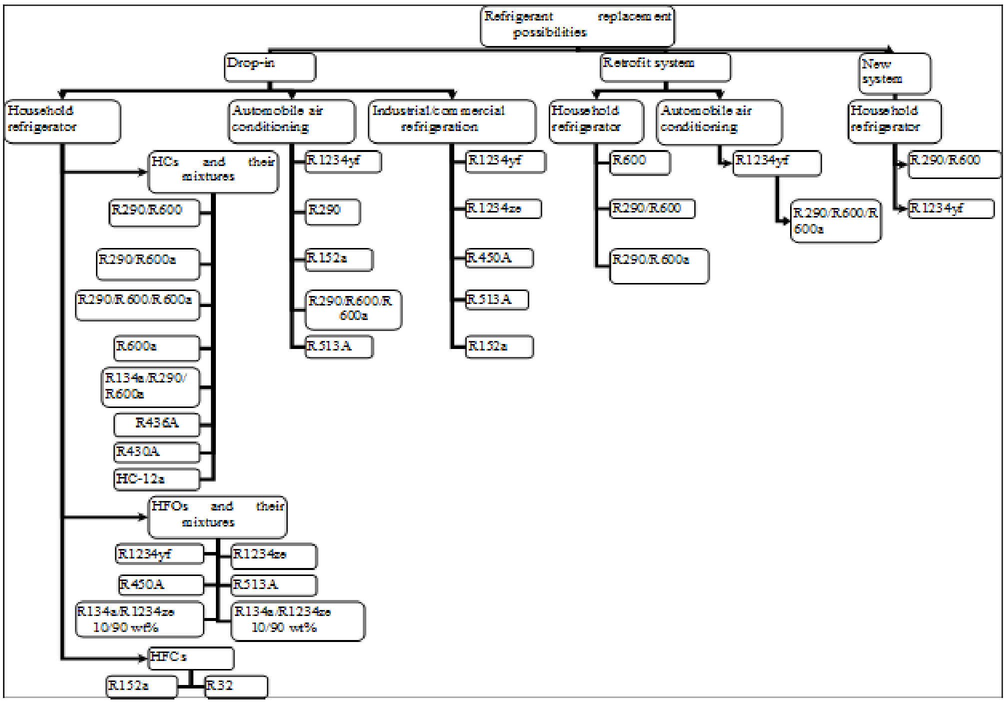

Figure 5. Different refrigerants replacement possibilities of R134a.

Household Refrigeration

Household refrigerators are the highest consumer of energy among refrigeration systems, where the residential electricity consumption by the refrigeration systems is approximately between 6%–30% of the energy produced worldwide [36,37]. Many studies have been conducted to find an environmentally friendly alternative to replace R134a with a better coefficient of performance (COP), low energy consumption, low GWP, and zero ODP.

HFOs Refrigerants and their Mixture as a Drop-in Replacement

HFOs are unsaturated HFC refrigerants. These refrigerants are more expensive than R134a, but they are environment friendly and have a shorter atmospheric lifetime as well as a GWP of less than 6. HFOs and their mixtures (R1234yf and R1234ze among them) were introduced as replacement refrigerants for R134a in the household refrigerator and the automobile air conditioning systems which were tested experimentally and theoretically.

Pure HFOs R1234yf and R1234ze(E) as a drop-in replacement

Many researchers have examined the behaviour of refrigerants R1234yf and R1234ze(E) to study their performance as low GWP alternatives of R134a refrigerant, in terms of energy consumption, cooling capacity, refrigerant charge, coefficient of performance and TEWI. For example, not limited, it was found that the annual energy consumption of a household R1234yf refrigerator-freezer was 1.9% higher than R134a as mentioned by Leighton [38], and the evaporator capacity and system efficiency decreased by 1.1% and 1.2%, respectively. Also, in this area, an experimental study by Karber et al. [39] using R1234ze(E) and R1234yf as a direct alternative to replacing R134a in a traditional household refrigerator (Ref1) and the second one is the current technology refrigerator (Ref2). Energy consumption values of R1234yf were higher with 2.7% of Ref1 and 1.3% of Ref2, whereas, R1234ze(E)'s power consumption values were 16% and 5.4% for Ref1 and Ref2 lower than that of R134a, respectively. While, from the theoretical and computational analysis implemented by Katare [40], the energy efficiency of R1234yf was minimal and the volumetric cooling capacity was very close to that of R134a, as well as that of R32 was 25.2% lower. In this context, the performance of a computerized vapour compression system with and without IHX, employing refrigerants R1234yf and R1234ze(E) as a substitute to R134a refrigerant were studied by Mota-Babiloni et al. [41]. They conducted experiments on a VCRS. Their results revealed that the cooling capacity, the average volumetric efficiency and COP values of R1234yf and R1234ze(E) without IHX were 9%, 30%, and 4%,5% and 7%, 6% respectively, lower compared to R134a. Also, with using IHX, the COP of R1234yf decreased between 3% and 11% and between 2% and 8% for R1234ze(E) compared to R134a. These results were approved by researchers Righetti et al. [42] through a performance analysis study conducted on a roll bond evaporator in a domestic refrigerator, due to both have a similar vaporization performance. It was also noted that the power consumption results of refrigerants R1234ze (E) and R1234yf, in the refrigeration facility used by Sánchez et al. [43], were 17.8% and (between 1.6-6.7%), in addition, they found a decrease in the cooling capacity was 24.9% and 4.5-8.6%, and COP was 8.6% and 10% respectively lower than that in the R134a system. It is worth noting that, the researchers now focus on using the R1234yf refrigerant in domestic refrigerators as a direct drop-in replacement, due to has similar thermodynamic properties to R134a. Regarding this subject, in a frost-free domestic refrigerator used by Aprea et al. [44], the resulting refrigeration capacity employing R1234yf was increased, with an energy saving of about 3% was obtained after 24 h of working with respect to R134a. In an experimental study on a household refrigerator by Aprea et al. [45], the results showed that the LCCP index has a more profound value than the TEWI index for R134a and HFO1234ze(E) refrigerants. In another work, Belman-Flores et al. [46] reported that the energy consumption of R1234yf was 4% and the TEWI was 1.07% higher than R134a one. The situation corresponds to a 92.2 g offers 7.8 % reduction in refrigerant charge. In a most recent study, using experimental data from a household refrigerator, Sieres and Santos [47] concluded that the R1234yf had a cooling power was 6%, the energy efficiency ratio values were 8% lower and the compression power values were 3% higher than that of R134a.

While, in related R1234ze(E), Aprea et al. [48] conducted a comparative analysis to evaluate the performance of R134a and HFO1234ze(E), in terms of pull-down and 1-day energy consumption, in a domestic refrigerator, initially designed to run with R134a. It has been reported that the pull-down time of R1234ze(E) was slightly greater than that of R134a by (+3.6%). The energy consumptions of the R1234ze refrigerator was slightly reduced, while the energy-saving after one day of working was about 9%. It was shown that there are lower evaporation and condensation pressure of HFO1234ze(E) than that of R134a.

It is known that the simulation models save time and effort and give approximate results, contribute to understanding the thermodynamic performance of refrigerants used in refrigeration applications, and many researchers have been simulated the refrigerants behaviour to reach approximate results. Among them are the authors Janković et al. [49], which developed a simulation model to study the performance of refrigerants R1234yf and R1234ze(E). Its results indicated that R1234yf and R1234ze(E) had 5-9% and 25-27% less cooling power and 2-10% and 4-7% less COP than they were in R134a, respectively. When changing the compressor to suit the cooling power of the system, the numerical results showed better performance as COP R1234ze(E) and R1234yf was around 2-5%, and around 6–12% less than R134a, respectively. In the same field, from the numerical and thermodynamic analysis associated with [50], with respect to the COP of R1234yf and R1234ze(E) decreased by 9.6% and 4.2% and the refrigeration capacity lowered by 19.8% and 26.6%, compared to R134a, respectively. However, the researchers Belman-Flores et al. [51] did not agree with previous studies on the use of refrigerant R1234yf with an optimal mass charge (92.2 g) as a direct drop-in alternative to the R134a(100 g), through conducting an energy and exergy analysis study for the domestic refrigerator under the assumed conditions. They proposed enhancing the COP and the energy efficiency of the system through the sub-cooling of the condensed liquid refrigerant.

Through aforementioned studies, regarding household refrigerators, it was revealed that although the refrigerant R1234ze(E) reduces energy consumption, at the same time, the cooling capacity is low, therefore it cannot be as a direct substitute for the refrigerant R134a unless the compressor displacement is modified to obtain a suitable mass flow rate [42], while the refrigerant R1234yf can be used as a direct drop-in replacement due to its performance that is largely compatible with that of R134a refrigerant.

HFC/HFO mixture as an Alternative Refrigerant

Aprea et al. [56] experimentally evaluated the energetic performances of binary mixture R1234ze(E)/R134a (90/10% weight) and pure HFO1234ze(E), in a domestic refrigerator designed for running with 100 g HFC134a. The pull downtime of the cycle in the case of using the binary mixture R134a/ R1234ze(E) was 4% lower than in the case of using R134a and 9.6% lower than in the case of using pure HFO. The energy-saving after one day of working with the mixture was 14% and with pure R1234ze was 5.6% compared with R134a. Table 3 summarizes some of the experimental studies of HFC/HFO mixture conducted around the world with household refrigerators.

HCs and their Mixture as a Drop-in Replacement

Hydrocarbons are environmentally friendly refrigerants that have good thermodynamic properties. HC mixtures are miscible with mineral oil and synthetic lubricants. Thus, the existing system using HFCs refrigerants can work with HCs mixtures as alternative refrigerants without any modification of the system lubricant oil. Many pure HC and their mixtures were investigated to replace the halogenated refrigerant R134a in refrigeration and Automobile air conditioner applications. Hydrocarbon refrigerants can be divided mainly into three categories are pure HC, HC blends, in addition to HC/HFC mixtures refrigerants.

Pure Hydrocarbons as Alternative Refrigerants

Numerous investigations have been undertaken to evaluate the performance of hydrocarbon refrigerants as an alternative to R134a in household refrigeration applications. It has been found that using an internal heat exchanger and R600a refrigerant improve the COP of a household refrigerator, as reported by Boorneni and Satyanarayana [57] in their experiment using a household refrigerator with a capacity of 165L, while the discharge temperature for R600a and R134a was lower using the heat exchanger than it is not used, for all reported evaporator temperatures. Qureshi and Bhatt [58] agree with the results obtained by the researchers Boorneni and Satyanarayana [57] when they used a household refrigerator with R600a (Isobutane) (50g) which gave lesser refrigerant mass by 66%, had a high COP, high refrigerating capacity and less energy consumption than R134a. Whereas, Sánchez et al. [43] used R290 in their experiment and found that the cooling capacity and COP were higher than those in R134a by 40.5–67.4% and 2.8-22.4%, respectively. The electric power consumed to run the compressor increased (up to 44.8%), which required the use of a compressor greater than that used in the case of R134a. It has been reported that R290 is not suitable for use as a direct drop-in replacement of R134a in the household refrigerator due to the low COP and high operating pressures.

Table 3. Experimental studies conducted around the world on HFOs refrigerants and their mixtures as alternatives of R134a in household refrigerators

References	Alternative	Results
[52]	R134a/ R1234yf (10:90, by wt.)	The pull-down time of binary mixture R134a/R1234yf was lower by 14%. Electrical energy consumed was lower by7.5%. Energy-saving was lower by 16%. Refrigerant charge was116 g, greater by16%.
[53]	R134a/R1234yf (10:90 by wt.) R134a/R1234ze(E) (10:90 by wt.) R1234ze(E), R1234yf	LCCP of binary mixture R134a/ R1234yf were lower by was 17%.
[54]	R134a/R1234yf (R513A) (44:56 by wt.)	Energy consumption was lower by 3.5%. Cooling capacity was higher. Optimal charge was 80 g, was lower by 5.9%.
[55]	R134a/R1234ze(E) (R450A) (42/58 wt.) R134a/1234yf (R513A) (44/56 wt.)	Mass flow rate of R450A was lower by 9.2%, Discharge temperature was 93.1 °C, Volumetric capacity was lower by 7%, Cooling capacity was 14.3% lower, COP was lower by 5.3%, Mass flow rate of R513A was higher by 19.3%, Discharge temperature was 88.9 °C, Volumetric capacity was higher by1.5%, Cooling capacity was higher by 2.5%, COP was greater by1.8%.

Hydrocarbon Mixtures and HFC/HC Mixtures as Alternative Refrigerants

Hydrocarbon mixtures are among the candidate alternatives that have attracted the interest of researchers as an environmentally friendly alternative to replacing the halogenated refrigerant R134. Where the researchers conducted many experimental studies to evaluate their performance, among them, Mani and Selladurai [59] used the HC refrigerant mixture R600a/ R290 (32/68 by wt. %) as a drop-in alternate for R134a in a VCR system. Their results revealed that the refrigerating capacity and electrical power consumption to running the compressor operates HC mixture was higher about 30.7–41% and 8.9–20% than R134a one, respectively. COP was higher compared to R134a. Similarly, Mohanraj et al. [60] declared that by using a mixture composed of R290 and R600a (45.2:54.8 by mass) for a wide domain of outside temperatures among 24 and 43 °C in a 200 L household refrigerator, pull-down time, ON time ratio and the energy consumption of hydrocarbon mixture, were lesser by about 11.6%, 13.2%, and 11.1%, respectively, The results of the experiments showed that a reduction of 45% of the HC mixture from charge requirement. Add to that the environmental impacts were lower than those of R134a, due to the decreased energy consumed to run the compressor using the hydrocarbon mixture. In the same field, an experimental study to assess the performance of a 220-litre home refrigerator using (R290/R600a, 50:50 by wt.) to replace R134a was conducted by Kathar and Surushe [61]. The refrigerant mass charge of mixture R290/R600a was nearly 50%, with refrigeration effect was higher by 35.29% and 12.5%, the compressor work was lower by about 9.12% and 14.68%, COP was higher by about 46.92% and 31.91%, and the discharge compressor temperature was less by 8K and 5K than R134a, without/with use of LSHX, respectively. Theoretically, Mohanraj [62] assessed the energy performance of a home refrigerator R430A (composed of 76% R152a and 24% R600a, mass ratio) at a wide range of the evaporator temperature (–30 to 0°C). The COP was higher by about 2.6–7.5%, the compressor discharge temperature was slightly higher (between 3 and 10 °C), the TEWI was lower by 7%, and the power consumption of the compressor was lesser with 1–9% for the R430A refrigerant mixture as compared with the similar quantities for R134a. Some of the experimental studies of HFC/HC mixture conducted around the world with household refrigerators have been summarized in table 4. With good system efficiency, HCs contribute to energy saving and can, therefore, be used as long-term replacements for household refrigerators refrigerants with some modifications of the system and solve safety issues related to their flammability.

HFC152a as an Alternative Refrigerant

The refrigerant R152a is an HFC refrigerant that has thermodynamic properties similar to the R134a refrigerant, in addition to its low global warming potential (138), so it attracted renewed global interest. Several studies have been done to test its performance as a direct drop-in alternative to R134a refrigerant in household refrigerator systems. One of these studies has been done by Bolaji [70], who examined experimentally, R152a refrigerant in the domestic refrigeration system to replace R134a. They found that the average COP R152a was 4.7% higher, with lower energy consumption, while the average COP R32 was 8.5% lower than the R134a. Also, a comparative study on energy and exergy performance of R152a and R134a, in a household refrigerator, have been made by Gaurav and Kumar [71]. The COP and the exergetic efficiency of R152a were greater than R134a one. By other work, it was found that the electrical power consumption, the mass flow rate controlled by the compressor and the refrigeration capacity of the HFC152a vapour compression system was lower by 16% or more, up to 41.5%, and 9.75% than those of R134a, respectively, and the COP of the R152a was greater than that of R134a by 11.70% and up to 13.20% when the system is working without/ with an IHX, as mentioned Cabello et al. [72]. Bhatkar et al. [73] experimentally tested R152a as an alternative to the R134a drop in a VCR system to investigate its performance with an aluminium microchannel type condenser. The experiment was conducted with operating conditions of evaporating temperature between –10 to 15 °C and condensing temperature 48 ° C. It was found that the refrigerant charge was lower by 40%, and the power consumption of the compressor was slightly lower and higher COP than that of R134a. Additionally, Raskar and Mutalikdesai [74] concluded that R152a in the vapour compression system showed 4.65% more COP. While Sánchez et al. [43] results, showed that the system refrigeration capacity with R152a was 5.7%, and the power consumption was 8.8% lower than the R134a system, furthermore, the COP was slightly improved from R152a, between 1% and 4.8%. The higher COP and low GWP are the main advantages of R152a, whereas, its main disadvantages are high discharge temperature and it is a flammable refrigerant compared to R134a. Based on these results, R152a may be considered as a better alternative to R134a, if safety means have been provided.

Automobile Air Conditioner System

Many researchers and investigators studied the performance of the automobile air conditioner system with alternative refrigerants. The schematic diagram of the automobile air conditioner system is revealed in Figure 6.

R1234yf and R134a/R1234yf Mixture as a Substitute to the R134 Refrigerant

Halogenated refrigerants used in automotive air conditioning systems contribute significantly to environmental pollution (the direct effect of refrigerant emissions) and climate change, in addition to carbon dioxide emissions (the indirect effect) by car exhausts in the atmosphere as a result of fossil fuel consumption [76]. The R1234yf refrigerant,

Table 4. Experimental studies around the world have been conducted on HCs refrigerants and their mixtures to replace R134a in household refrigerators

References	Alternatives	Conclusions
[63]	R290/R600a mixture (50:50 by wt.)	Refrigerating capacity of R290/R600a was higher. The total consumed energy was lower by 4.4%. Mass of refrigerant is reduced by 40%.
[64]	R290/R600/R600a mixture (24.4: 56.4: 17.2 by wt.)	The electric energy consumption of R290/R600/R600a mixture was lower by 7.6%. Pull-down time was lower by 5.5%. Pressure ratio was lower by 4.3%. Actual COP was 7.6% higher.
[65]	R436A (R290/R600a mixture) (56:44 by % wt.)	Charge amount of R436A was lower by 48%. ON time ratio lower by 13%. Energy consumption was lower by 5.3 %. TEWI was lower by 11.8%.
[66]	HC-12a	COP of HC-12a was greater, Energy consumption was lesser The latent heat of vaporization was greater The amount of refrigerant charge was lesser.
[67]	R290/600a mixture (50:50 by wt.)	The cooling capacity of the zeotropic mixture R290/R600a was higher. COP of the system was higher. The electric power was much lower. The charge mass amount was much lower. The optimum charge was 60 g.
[68]	R290/R600a (60:40 by wt. %) And (50:50 by wt. %).	COP of refrigerant R600a/R290 was higher by 53.1- 72.3%. Refrigerating effect was higher by 10- 35.8%. Energy consumption was lower by 39.2- 43.3%.
[69]	5-HC mixtures (R134a/R290/R600/R600a) The mixture-2 with mass ratio was (15:40: 40:5 by wt. %)	The actual COP of the mixture-2 refrigerator was higher by about 8.1%. Good alternative refrigerant to replace R134a.

which has a 100-year time horizon GWP ≈4, has gained important consideration as a good substitute refrigerant for global automobile air conditioners applications. However, R1234yf can be equally well used in real-life technologies like fixed refrigeration applications. Regarding this matter, in an automobile air conditioning bench tester system used by Lee and Jung [77], R1234yf refrigeration capacity under summer air-conditioning conditions had been up to 4.0%, COP 2.7%, compressor discharge temperatures 6.7 °C and charge mass amount was about 11% lower than those obtained from R134a, under drop-in substitute conditions. Navarro et al. [78] concluded that the R1234yf refrigerant in an automotive system with an open piston compressor gave about 10-15% lesser cooling capacity, the discharge temperature was lower by 10K, and lower heat loss than R134a. The thermal physical properties of R1234yf are very similar to the properties of R134a in the evaporator core, as a study by Rajamanickam et al. [79] under specific operating conditions, with identical results for heat load and outgoing refrigerant temperature. A comparison study had been conducted by Golzari et al. [80] to determine the possibility of using HFO-1234yf instead of R134a in the AAC system. It was observed that COP achieved the compressor used HFO-1234yf 15.5% higher by applying the energy method and 19.8% by employing the entropy method than that of R134a. While, Vaghela [81] found that the COP of R1234yf was 6.3% and the discharge temperature was 16 % lesser compared to R134a. Table 5 summarizes some of the experimental studies of HFO1234yf and R134a/R1234yf conducted around the world with automobile air conditioner.

Hydrocarbons as a Drop-in Replacement to R134a

Several researchers have targeted greenhouse gases such as the traditional R134a refrigerant used in AAC systems and have recommended the use of low-GWP refrigerants such as hydrocarbons to reduce environmental impacts. When the refrigerant R290 was used by Navarro et al. [78],

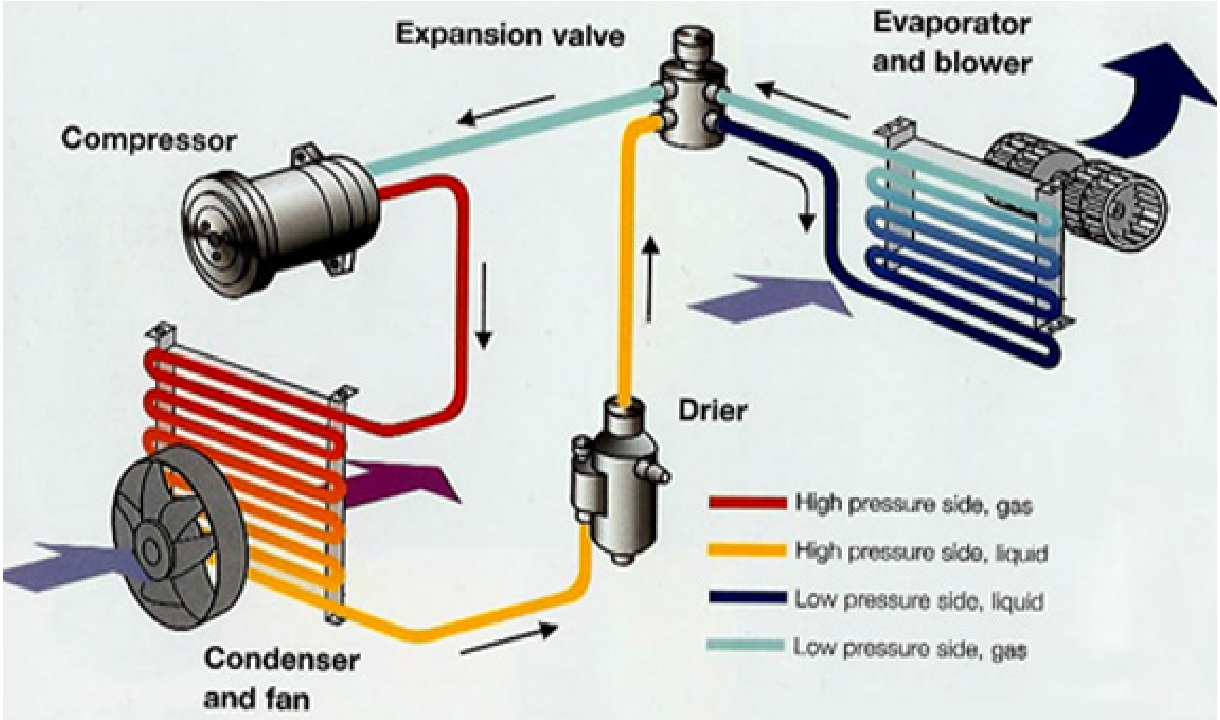

Figure 6. Schematic diagram of the automobile air conditioner [75].

Table 5. Experimental studies conducted using HFOs and their mixtures to replace R134a in automobile air conditioners

References	Alternative	Conclusion
[82]	R1234yf	Optimum charge amount of R1234yf was about 95%. COP was lower by 9%. Cooling capacity was 12.4% lower.
[83]	R1234yf	COP lower between 0-27%, The performance of heat transfer in evaporator was similar, whereas, in case of the condenser was lesser. The system's volumetric efficiency was slightly inferior.
[84]	R1234yf/R134a mixture (89:11 by wt.)	In cooling mode Refrigeration capacity of R1234yf/R134a was similar. COP was lower by 4–9%, Discharge temperature of the compressor was lesser by 10 °C. Higher mean volumetric efficiency was higher by 5%. In heating mode The average heating capacity was reduced by 3%. COP was lower by 4–16%. The average volumetric efficiency increased by nearly 5% for R1234yf/R14a.

it was concluded that volumetric efficiency and compressor efficiency improved by 30%, 15%, respectively, compared to R134a refrigerant in all tested conditions. In another experimental study on an automobile air conditioning system using hydrocarbon mixture refrigerant (R290/R600)/R600a) by Dahlan et al. [85], it was noted that the fuel consumption and performance characteristics improved positively, with higher COP and higher cooling capacity for the hydrocarbon mixture refrigerant against R134a in a similar operating condition. As it turned out, in terms of COP, and according to the theoretical evaluation of the AAC system using R290 and R600a refrigerants by Vaghela [81], they were 2.4% lower and 3% higher, and the compressor discharge temperature was 2.1% and 12% lower, respectively, for both refrigerants than those of R134a. The refrigerants R290 and R600a are highly flammable and thus cannot be used as a substitute for R134a in the AAC system unless the safety issues are diminished and addressed.

Commercial Refrigeration System

Theoretically and experimentally, many researchers have studied the performance of low GWP refrigerants as a drop-in replacement of R134a in commercial refrigeration. One of the main parameters for evaluating refrigerants performance as environmentally friendly refrigerants, is electrical energy consumption. Three low-GWP working fluids were experimented by Mota-Babiloni [86] in a large commercial refrigeration system. Belman-Flores et al. [87] developed an ANN model to simulate the small-capacity cooling system Their results exhibited that the cooling capacity using R1234yf, R1234ze(E) and R450A was lower by around 10%, 30%, and 6%, respectively, with a lower power consumption of R450A mixture at the same cooling capacity, compared to R134a performance. It was observed that the cooling capacity and electrical power consumed by the R450A refrigerant was lower by 10%, while it was quite the same as R513A compared to R134a, at similar quantities for all refrigerants. The simulated COP values showed a behaviour similar to all three refrigerants. The R450A (R134a /HFO-R1234ze zeotropic mixture, 42%:58% by wt.) was tested in a small refrigeration capacity test bench by Makhnatch et al. [88]. The cooling capacity was 9.9%, and COP was 2.9% lower of R450A than in R134a, with an inferior reduction in the values of discharge temperature and power consumed by the compressor. In an experiment to evaluate the performance of R513A and R450A refrigerants in a commercial refrigeration system, researchers Llopis et al. [89] found an increase in electrical energy consumption of R513A around -1.6% - 1.2%, while in the case of R450A the increase was between 1.3-6.8%. The fluids R134a, R513A were experimentally tested in a refrigeration test bench by Mota-Babiloni et al. [9], their results showed that the power consumption of R513A was greater, the COP was 5% higher, and the cooling capacity was higher than R134a. In the most recent study, Sánchez et al. [90] performed experimental analysis from the point of view of the energy impact using R134a, R152a and R1234ze(E) in a commercial glass door cabinet. The total energy consumed for one day with an indirect expansion configuration was increased by 21.8% for R134a, 18.7% for R152a and 27.2% for HFO-1234ze(E). The mass charge of these refrigerants had been reduced up to 42.5%, 62.0% and 52.3%, respectively. The refrigeration capacity of the refrigerating system was reduced from 1.57% for R152a to 32.51% using R1234ze(E) with an increased compressor operating time by 46.4% as their results demonstrated. As the conclusion of this option, the refrigerant R1234yf can be considered as a promising long-term eco-friendly solution in the future with some minor changes in the household refrigerators and automobile air conditioning (AAC) systems.

Replacement Scenario as a Retrofit Refrigerant

The retrofit refrigerant is the second option, in which the cooling system is recharging with alternative refrigerant, after removing the original refrigerant with minor modifications. The modifications of the system may include, the expansion devices, lubrication oil and some other specific components, to solve the compatibility issues that are facing the substitution process of new refrigerants [3].

The household refrigerator as a retrofit system

Many researchers have investigated the performance of domestic refrigerators using HCs and their mixtures as an alternative to replacing R134a. Mohanraj et al. [91] conducted an experimental study to apply the hydrocarbon (HC) mixture (45 % R290 and 55 % R600a, mass ratio) in a 165-litre domestic refrigerator system. It was found that COP was about 6.4-12.7 % higher, the discharge temperatures were about 7-18 °C lower and energy consumptions per day were by 1.6- 4.3 % lower than those obtained using R134a.

Joybari et al. [92] carried out an exergy analysis with 60 g of R600a to evaluate the performance of a home refrigerator originally designed to work with 145 g of R134a. The experiment was designed by applying the Taguchi method to reduce exergy destruction. It has been proven that the greatest destruction of exergy occurred with a charge of 145 g of R134a in the compressor. The authors reported that the optimum charge amount is 50 g of R600a refrigerant, which is about 66% less than R134a refrigerant. This compresses costs and reduces the flammability of R600a refrigerant. Theoretically, the performance of modified household refrigerators/freezers using a zeotropic blend (R290/R600a) had been studied by Liu et al. [93]. They found that the COP was improved by 16.71%, while the improvement in volumetric cooling capacity was 34.97% compared to the refrigerant R134a. Raveendran and Sekhar [94] experimentally studied the performance of the brazed plate heat exchanger as a condenser in a modified domestic refrigeration system utilizing hydrocarbon mixture R290/R600a instead of R134a. The modified system had COP 52-68% higher, with 21-27% less energy consumption and 21% less TEWI compared to the traditional R134a system. Mota-Babiloni[95] experimentally evaluated the performance of the VCR test bench at different operating conditions using R1234ze(E) as an alternative refrigerant of R134a. It was found that the cooling capacity can be improved via using an internal heat exchanger with a compressor that is greater by 43% than that use with R134a. Recently, in a study using R1234yf, it was found that the COP improved by 20% compared to R134a with the addition of an integrated ejector for the refrigeration system, as reported by Yilmaz and Erdinç [96]. Some of the experimental studies of retrofitted refrigerants conducted around the world with household refrigerators have been summarized in Table 6.

Table 6. Experimental studies of HCs and their mixtures as retrofitted refrigerants of R134a in household refrigerators

References	Alternative	Results of experimental studies
[97]	R436A (R600a/R290 mixture, 46:54, by wt.) And, R600a	For the R134a type compressor. Energy consumption of R436A was lower by 14%, Optimum charges of refrigerant (55 g). Energy consumption of R600a was lower by 7%, Optimum charges of refrigerant (60 g). For the R600a type compressor. The energy consumption of R436A was lower by 14.6%. The energy consumption of R600a was reported to be 18.7%. The optimum charge refrigerant (50g both).
[98]	R290 / R600a Hydrocarbon mixtures, in the ratio by mass, (HC1, 65:35) (HC2, 50: 50) (HC3, 0:100)	The power consumption was greater with no-load pull-down test. The optimal mass charge was 40% for all HC refrigerants. After recalculated capillary tube, The power consumption was lower with one-day on-load cycling test. The energy factors (EFs) were higher by 9.1%, for HC1, by 12.2%, for HC2, by 42.3%, for HC3.
[99]	R513A mixture (R134a/R1234yf 44:56 by mass)	Cooling capacity was improved up to 5.6% with IHX. The power consumption was slightly decreased. COP was increased up to 8%.
[100]	R1234yf	The COP of an oil-free VCR system with R1234yf was 20% lower. Volumetric efficiency was 5% lower.

Automobile air conditioners as a retrofit system

Numerous theoretical and experimental studies have been done to examine and identify the new R134a alternative refrigerants in Automobile air conditioners by many researchers around the world. Among them, Zhao et al. [101] simulated using the effectiveness-NTU method to estimate the performance of the heat transfer rate of a mini-channel evaporator, under normal working conditions. It was reported that the heat transfer coefficient in the evaporator (two-phase zone) has a higher value of R134a compared to the case of R1234yf. Whereas, the hydrocarbon mixture (composed of R290, R600 and R600a) was used by Perang et al. [102] to carry out an experimental study to assess the performance characteristics of the current air conditioning system of cars, works with the R134a. It has been indicated that the hydrocarbon mixture achieved a positive enhancement in performance characteristics in terms of power consumption, temperature distribution and COP, compared with HFC-134a. Consequently, it is suggested that the hydrocarbon mixture refrigerant type is an alternative for the current HFC-134a applied in the automotive industry. After two years, Gaura and Kumar [103] used an alternate refrigerant R1234yf as a working fluid to replace R134a refrigerant. It was found that the reduction in the system of the compression ratio, the load and temperature lead to reducing the flammability of R1234yf. The authors reported that the cooling time of refrigerant R1234yf was inferior to that of R134a with a decrease in the range from 4% to 6%.

Replacement scenario of refrigerants as a new system

The new system is the last option when the original equipment replaces with a new one specially designed to work with alternative refrigerants [3].

The household refrigerator as new system

There are a few studies about this option,[104] had been evaluated the energy performance of single-phase VCR system using refrigerants R1234ze(E), R1234yf. Compared to R134a, the COP of the basic cycle operating with R1234yf was 4-8% lower, and the cooling capacity was 4- 7% lower. Whereas the COP of those systems operating with R1234ze was similar and the cooling capacity was lesser by 25-27%. All studies have reported that R1234ze(E) can be used in R134a systems after making some modifications to maintain energy performance. On a similar topic, Yan et al. [105] concluded from the results of their theoretical study in a freezer with (R290/R600a) mixture, that the volumetric refrigeration capacity and COP of the modified ejector expansion refrigeration cycle were higher by 4.5% and 56.0% than those of basic throttling cycle, respectively. In the same field, Chen et al. [106] theoretically analyzed a modified vapour compression cycle employing HC-zeotropic mixture R290/R600 for freezers. They concluded that the HC mixture exhibited COP was by 8.9% and 12.4% higher volumetric cooling capacity compared to the traditional vapour compression cycle. In recent years, an experimental study using the R290/R600a mixture (60:40, by mass) in a household refrigerator by Pilla et al. [107]. They mentioned that the refrigerant mixture had better COP performance, compressor discharge temperature, power consumption, mass flow rate and Carnot COP.

RESULTS AND DISCUSSION

In this work, the results of the comprehensive review of all alternative refrigerants were compared with the R134a in three categories which are domestic and commercial refrigeration and automobile air conditioners, up to now. The alternative refrigerants used to replace R134a are divided into six groups: purely HFCs, pure HFOs, R134a/HFOs mixtures, pure HC mixtures, HC, and R134a/HC mixtures. This comprehensive review has been focused on several parameters in detail such as COP, cooling capacity, discharge temperature, mass flow rate, pull downtime and cooling capacity of the systems when employing alternative refrigerants to the high GWP refrigerants. A comparison of the results of various studies that based on the percentage of the energy consumption (%), the reduction in the refrigerant charge (%) and improvement in COP (%), utilizing many refrigerants as replacement of R134a are shown in Figure 7 (a and b) and Figure 8.

In terms of drop-in replacement, the performance results of the domestic/commercial refrigeration system showed a decrease in the COP using R1234yf, R1234ze and R513A, with higher COP using R450A as alternative refrigerants of R134a at dissimilar operating conditions. R1234ze(E) and R1234yf offer some advantages as working fluid in various refrigeration systems in comparison to R134a, where they are classified as non-toxic and low flammable (A2L). R1234ze(E) is non-flammable at specific temperature and humidity conditions but its cooling capacity is lower, therefore, it cannot be used as a direct drop-in replacement of R134a.

The lower energy efficiency of HFOs can cause a higher indirect global warming increase than direct global warming reduction when compared to R134a. Using an internal heat exchanger (IHX), the component produced a positive effect in R1234yf (around 1% increase in COP difference considering R134a as the baseline refrigerant. Also, outcomes exhibited that electrical energy consumption was enhancement by utilizing R134a/R1234ze(E) (wt. 10/90%), R1234ze(E) and R513A refrigerants with higher energy consumption of R1234yf by 1.6-10%. Therefore, the refrigerant R513A had the best performance compared to R134a at the low condensing and evaporating temperatures and no risk potential from oil degradation because its discharge temperature is dropped. R513A is classified as non-toxic, non-flammable (A1) by ASHRAE and has a similar Normal boiling point to that of R134a. From the point of view of energy efficiency and reducing global warming potential, the R513A in air conditioning and refrigeration systems can be recommended as a drop-in replacement of R134a with a minor adjustment of the Thermal Expansion Valve. R450A can be used as an alternative to R134a with only minor modifications of the commercial refrigeration system. It has been found that the new mixture R450A could reduce energy consumption, for the same cooling capacity. Although the values of the GWP of R513A and R450A are reduced between 56% and 58% concerning to R134a, these refrigerants are considered as a short-term option from an environmental point of view because they do

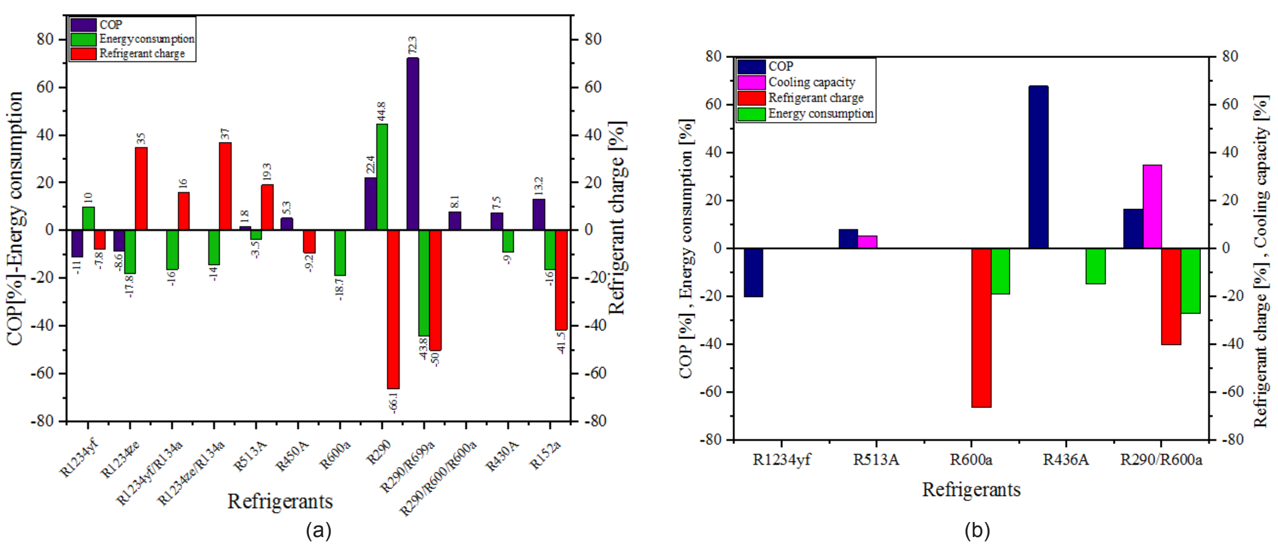

Figure 7. Percentage difference in COP, energy consumption and refrigerant charge of alternative refrigerants and their mixtures: (a) drop-in replacement, (b) Retrofit Refrigerant of R134a in a domestic refrigerator.

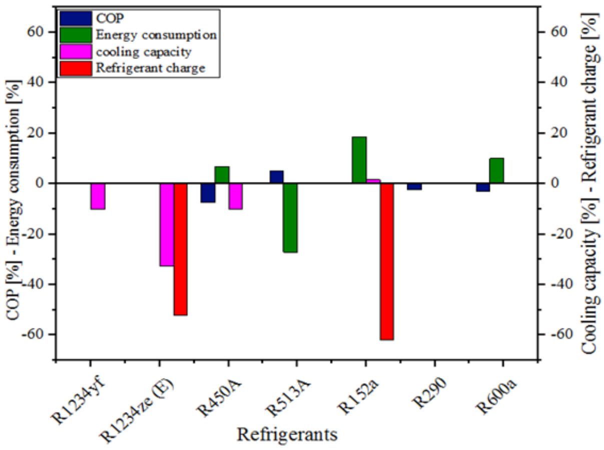

Figure 8. Percentage difference in COP, energy consumption, refrigerant charge, and cooling capacity of alternative refrigerants as a drop-in replacement of R134a in a commercial refrigerator.

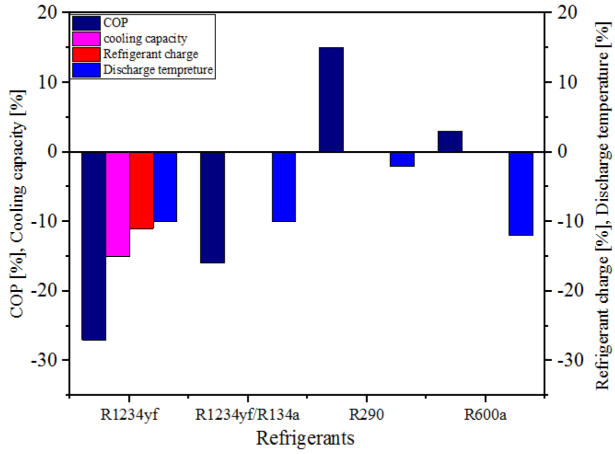

Figure 9. COP enhancement, refrigerant charge, cooling capacity, and discharge temperature of alternative refrigerants used to replace R134a in automobile air conditioners.

not meet the EU F-gas regulation. The cooling capacity of most alternative refrigerants are somewhat close together to R134a, except R1234ze had a significantly lower cooling capacity, which means the impossibility use it as a direct drop-in replacement of R134a. The (HFC134a/HFO1234yf (10/90%weight)) as refrigerant mixture led to a lessening in the electrical power consumed during the lessening of pull-down tests with the optimal charge 116 g of the refrigerant mixture with respect to HFC134a. Non-flammability and lesser cost are additional benefits advantages of the refrigerant mixture compared to pure HFO1234yf. The hydrofluorocarbons R152a revealed a reduction in cooling capacity between 1.57 and 9.75%, and the consumption of electric power by compressor decreased by 8.8 to 16%. Whereas, there is an increment of the total energy consumption for 1 day with indirect expansion configuration by 18.7% in commercial facilities. When the system operates without an IHX, generally the COP in the case of R152a is greater than in the case of R134a, while the electrical power input, the mass flow rate handled by the compressor and the refrigeration capacity of R152a are lower than those of R134a. If the system is modified with an IHX, the COP could increase up to 13.20%, in the case of using R152a, compared to R134a.

HCs refrigerants have many advantages that make them a good alternative to R134a: they are environment friendly, have good compatibility with mineral oil and have good performance in terms of COP, energy efficiency, compressor discharge temperature and cooling capacity. Furthermore, the system with HCs and their mixtures had lower amounts of refrigerant charge because it has a low liquid density compared to R134a one. That help to reduce the emission of the refrigerant in the atmospheric layers. The system with pure HC, HC mixture and HC/HFC mixture had higher COP by 2.8-22.4%, 3.6-72.3% and 8.1 % as compared with the conventional refrigerant R134a, respectively. The HC600a (isobutane) refrigerant showed similar evaporation performance to HFC134a. Thus, it can be considered an eco-friendly alternative to HFC134a. The most effective parameter was the charge amount of R600a, for that needs change the compressor. The optimum charge amount required for R600a is 50 g (66 % lower than that of R134). It was observed a greater cooling capacity, and consumption of the electrical power by the compressor was significantly reduced (between 3-18.7%) mainly due to its low specific volume. Using an internal heat exchanger and R600a refrigerant improve the COP of a household refrigerator. The main disadvantage of using the R600a as an alternative refrigerant in household refrigerators is their flammability, thus, the restrictions of the safety requirements related to the amount of refrigerant charge should be taken into consideration. The system with refrigerant R290 has energy consumption up to 44.8% more than R134a. Also, the COP of Pure HC, HC mixture and HC/HFC mixture was more significant than R134a.

Figure 9. Shows the COP enhancement, refrigerant charge, cooling capacity, and discharge temperature of alternative refrigerants used to replace R134a in automobile air conditioners. In automobile air conditioners the refrigerant R1234yf shows drop-in terms of refrigeration capacity in the range of 3-12.4%, the COP of R1234yf was reduced by 0.8-27% compared to R134a, this is because the performance of the system employing R-134a and R1234yf is affected by many conditions, including the refrigerant charge, the heat transfer performance in the evaporator and condenser, the expansion device, the addition of an internal heat exchanger, a compressor. Adding an internal heat exchanger can optimize the COP R1234yf system. The compressor discharge temperature is lower with about 6.4-10°C

in the case of R1234yf compared to R134a. The volumetric efficiency was slightly lower for the R-1234yf system. In the car air conditioning, the R1234yf / R134a has a similar cooling capacity to R134a and the COP was 4-16% lower, the average volumetric efficiency was higher by 5%, and the average discharge temperature of the compressor was lower by 10 °C than that of R134a.

CONCLUSIONS

The literature survey provides information on several alternative refrigerants available and their blends that was already considered to assess their performance, with advantages and disadvantages, as a drop-in replacement or as retrofit refrigerants to replace R134 in existing traditional household/ commercial refrigerators, Automobile air conditioner appliances. From the experimental and theoretical results presented in this review, the following results were extracted for each refrigerant:

- The authors concluded that R1234yf is a good drop-in alternative to R134a in a household refrigeration system.
- Using R1234ze(E) involves some modifications to the refrigeration system to compensate for its low capacity, thus making it a less suitable candidate as a drop-in replacement for R134a, even if it showed lower energy consumption but can be a good option only in new systems.
- The HFC134a/HFO1234yf mixture could be used as the best drop-in substitute for HFC134a in existing appliances. Furthermore, the mixture became non-flammable and less expensive.
- R1234yf and R1234yf/R134a can be considered as a promising long-term eco-friendly solution in the future, asking for some minor changes in the AACs system.
- R450A can be adopted as an alternative refrigerant mixture to R134a with minor modification of the system.
- The refrigerant mixture R513A is the best drop-in refrigerant fluid of HFC134a in existing home refrigerator appliances.
- Although the R450A and 513A as HFC/HFO blends have performance values and very similar properties to R134a, they did not meet the EU F-gas regulation requirements due to their high GWP (more than 500).
- These results indicated that the R152a could be used successfully as a drop-in substitute of R134a refrigerant in a vapour compression system.
- If the safety issue is solved concerning flammability, the HC and their mixtures could be considered the best long-term alternative to HFC134a.
- The HC refrigerants R290, R600a and HFO-R1234ze are not suitable as a direct alternative to the R134a.
- R-290 refrigerant is a good alternative to R134a, in Automobile air conditioner systems with considering their high flammability issue.
- HFC-R32 can be employed as a working fluid in domestic refrigerators in the immediate future.

Finally, based on the literature reviewed, one can say that the HCs refrigerants and their mixtures, R1234ze(E) are not suitable to replace R134a as a direct drop-in option. R1234ze(E) may be used as an ozone-friendly, user-friendly, energy-efficient, safe and cost-effective substitute refrigerant to replacing HFC-134a with some substantial modifications in the existing refrigeration systems. R1234yf, R152a, R450A and R513A are the best drop-in replacement fluid of HFC134a in the existing domestic refrigerator and Automobile air conditioner appliances. As discussed above the most refrigerants showed a good performance at various boundary conditions.

ABBREVIATIONS

ANN	artificial neural network
AAC	automobile air conditioner
CFCs	chlorofluorocarbons
CR	commercial refrigeration
COP	coefficient of performance
EFs	Energy factors
GWP	global warming potential [$kgCO_2kg_{ref}^{-1}$]
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
HFOs	hydro fluoro olefins
HCs	hydrocarbons
HR	household refrigeration
IHX	internal heat exchanger
LCCP	life cycle climate performance
LSHX	line suction heat exchanger
ODP	ozone depletion potential
ODSs	ozone depletion substances
TEWI	total equivalent warming impact [$kgCO_2eq$]
UNEP	United Nations Environment Program
UV	ultraviolet
VCR	vapour compression refrigeration

Nomenclature

E	annual energy consumption [kWh/year]
L	annual emissions of fluid [kgref/year]
m	charge mass of refrigerant [kgref]
n	life of the operating system

Greek symbols

α	recovery/recycling factor from 0 to 1.
β	indirect emission factor (emission for per kWh electricity Generation) [$kgCO_2$/kWh].

Subscripts

ref	refrigerant

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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