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Comparative Study on Evaporative Cooling, Air Conditioning, and Environment-Friendly Refrigerants

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Abstract

In this research article, a complete analysis of the thermodynamic performance of various refrigerants in air conditioning units is presented, along with a system of evaporative air conditioning that has been suggested for use in a variety of climate situations, including moderately dry, hot, and arid, and humid climates. Most air conditioning systems use refrigerants such as R22 and R407C, which must be phased out due to their adverse effect on the environment like ozone depletion, greenhouse effect climate change, etc. as per the Montreal Protocol and Kyoto Protocol. The current literature survey presents that refrigerants R1234yf and R1234ze (e) are a more reliable long-term replacement for R22 in air conditioners. In the world, 15% of the total electricity consumption is used in VCR-based systems and these cooling systems are responsible for increasing global warming by 10% globally. In scenarios of 2040, overall energy consumption will grow by 10% per person, as per the International Energy Agency (IEA 2021). Thus, this research study also comprehensively assesses energy-efficient cooling systems at minimum cost. Evaporative cooling systems are quite effective and can be used with liquid or solid desiccant units to maintain various climatic zones. The novel solution is better than the air conditioning system from the cost point of view.

Keywords: Air Conditioning System, Climate, Cooling Systems, Energy-Efficient Technology, New Eco-Friendly Refrigerants.

Introduction

As global warming of the environment, continuously rises due to the greenhouse effect, thus the need and utility of energy-efficient cooling systems have increased in the last few decades. There are several places where cooling systems are required to generate the perfect human comfort in hot climate conditions, such as offices, malls, automobiles, cinema halls, hospitals, industries, hotels, auditoriums, ships, etc. Human beings may face many problems like heat stroke, dehydration, and hyperthermia, which can be prevented by using conditioned air i.e. filtration, humidification, cooling, and disinfection from cooling systems. On the other hand, few kinds of literature surveys show that cold and dry air supply to the conditioned space may create a possible adverse effect on the human body such as: i) some people may face the problem of skin irritation and eye itching due to excessive air conditioning, ii) people may experience respiratory conditions such as bronchitis, asthma, and general dehydration as a result of breathing dry air, iii) peoples of all age group are facing the serious health issue i.e. joint pain due to dry of synovial fluids of joints since after spending a long time in dry air. As air with the condition of cold and dry, supplied to conditioned spaces throughout hot and dry climates does not create a comfortable humid environment inside to reduce this problem a direct evaporative cooler can be assembled along with air conditioning system. According to the Indian hot climate conditions, only a cooler is not sufficient to reduce the temperature of a conditioned space, and by using only air conditioner, the human body will face various health issues as discussed above. Therefore, employing a combination system comprising an air conditioner and a direct evaporative cooler is preferable to achieve the desired level of human comfort. Several researchers have studied the performance of direct evaporative coolers (DEC), indirect evaporative coolers, and air conditioning systems by using the tools experimentally or theoretically. A mathematical model developed for using a DEC system in an experimental setting in a Brazilian metropolis concluded that this system has a lot of promise for comfort and may be a good replacement for an air conditioning system (1).

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Focused on the risk factors of HVAC systems for US office buildings and described the causes as a result of which the human body may face many problems of health joint pain asthma, general dehydration, etc. (2). The effectiveness of a two-stage indirect/direct evaporative cooler is experimentally examined under a range of climatic situations and their findings showed that this system can satisfy the requirements of traditional vapor compression refrigeration systems (3). The calculus-based modeling presented analyzes the heat and mass transfer in a DEC and ascertains the effects of various parameters on the cooling efficiency of the DEC, including inlet frontal air velocity, the thickness of pad module, inlet air T_d, and T_w, and inlet air velocity (4). A theoretical assessment of the exchange of mass and energy between a water layer and air in a DEC system presented and concluded that frontal air velocity and pad module thickness are the two key factors that affect cooling efficiency (5). A hybrid system that combines direct evaporative cooling, cooling coils, and nocturnal radiative cooling has been presented, and found that the proposed hybrid system could be a good replacement for VCR systems, in Tehran city (6). Experimental analysis of the indirect evaporative cooler for four Iranian cities has been performed and found that this installation can cut the cooling load by up to 75% throughout winter seasons (7). A unique dew point evaporative cooler together with an air conditioning system has been presented, and experiments were conducted to evaluate the performance of the cooler under different inlet air conditions and its impact on the exiting air (8). The innovative dew point evaporative cooling system was theoretically analyzed for a variety of intake air conditions, including dry, mild, and humid environments (9). A trial investigation highlighted the use of efficient evaporative cooling technologies to decrease the temperature of incoming air devoid of adding dampness, providing a solution to lower peak electrical loads and greenhouse gas emissions from space cooling (10). A numerical model analyzed the impact of inlet frontal air velocity, pad thickness, inlet temperature T_d on DEC cooling efficiency, showing its compatibility with air conditioners using high-efficiency pads (11). In an experimental study, the frontal air speed, frontal air temperature, and incoming water temperature of a DEC unit were examined (12). The economic feasibility of a hybrid air conditioner and DEC is theoretically examined with an emphasis on the low cost of power usage (13). The performance of an evaporative cooling system was theoretically assessed for various cooling pad shapes and materials and found that efficiency varies with air mass flow rate (14). DE and IEC evaporative cooling system with a 100% outdoor air system, whose main unit was established in a building, was experimentally tested for performance and concluded that this system would function during the intermediate season (15). Analyzed the performance of an air-cooled HX with six distinct water curtains in a series utilized as wetted pads at spray water flow rates of 0.005-0.01 kg/s, air speeds of 0.6-2.4 m/s, and run times of 0–72 h (16). The performance of the air conditioning system and evaporative cooling condenser are experimentally investigated to increase the COP (17). After evaluating the Maisotsenko performance of HMX, it was determined that employing an evaporative unit in addition to an air conditioner was preferable (18). Experimental and mathematical approaches were used to evaluate the efficiency and refrigeration capacity of the novel cross-flow M-cycle under a variety of operational and climatic conditions and found that air conditioning applications can use M-cycle heat exchangers (19). A hybrid system of a VCR system and an IEC was presented, demonstrating that using an IEC with an air conditioner reduces cooling load and electricity consumption (20).The Maisotsenko Cycle heat exchangers for different air conditioning applications have been analyzed mathematically by simulation (21). The evaporative unit has a greater capacity to save electricity in hot and dry weather based on their analysis of energy technologies for evaporative types of cooling systems (22). Based on the theoretical research of the combined system of DEC and air conditioning unit, determined that it performs well in dry and moderately humid environment conditions but is not appropriate for extremely humid weather (23). In Bhopal, India, an experimental study of a combined DEC and VCR-based air conditioning system demonstrated that VCRs can be used with direct evaporative coolers in a variety of climates (24). An experimental investigation of the cooling capacity of a cross-flow DPEC revealed that it performed well in hotter regions but that its effectiveness decreased in humid environments because of its low evaporation rates (25). A thorough review presented on advanced technologies such as radiative cooling systems, cold energy storage plants, temperature and THIC, defrosting and frost-free, and GSHP, etc. because the demand for cooling systems will grow tenfold by 2050 (26). A theoretical model was used to explore the analysis of DEC unit in hot and arid weather and determine that there is no discernible role for the effectiveness of cooler on exergy efficiency, and it can be obtained as 0.7-0.8 for summer weather for the studied location (27).

This article found that evaporative cooling systems, both direct and indirect, and conventional air conditioners are used for human comfort in a wide range of applications and climates. However, a hybrid technique that incorporates both conventional air conditioning and direct evaporative cooling seeks to reduce the potential health concerns associated with long-term air conditioning usage. While this hybrid approach works well in hot, dry settings, it struggles to hold its own in damper environments. More investigation into the long-term effects of air conditioning on human health is required, especially in regions with widely fluctuating humidity levels, and less is known about how well hybrid cooling systems work in humid climates. In Table 1 we can see a compilation of literature that shows how cooling strategies have evolved for different climates and what those approaches have found.

Table 1: Evaluations of Vapour Compression System, Direct and Indirect Evaporative Cooling Systems

Author	Technique of Work	Cooling Methods	Climate that Applied	Conclusion
Delfani *et al.*, (7)	Experimenting	IEC + CCC	● Hot and dry, ● Hot and humid	The suggested method can lower the cooling demand by up to 75% during the cold season by using an IEC system to pre-cool the air for traditional air conditioning systems. Additionally, it is possible to cut the electrical energy usage of packaged unit air conditioners by roughly 55%.
Jain *et al.*, (13)	Theoretical	DEC+CCC	● All seasons	In some parts of India, hybrid systems might be a financially appealing solution for specific applications such as high-density offices, low-density offices, movie theaters, and waiting areas, and lower yearly electricity costs.
Kim and Jeong (15)	Experimenting	IEC + CCC	● Hot and humid	As used in two-stage mode during the intermediate season, IDECOAS reduces electricity consumption by 51% than the traditional VAV system. Due to insufficient sensible cooling at the IEC, the suggested system might require 36% more energy than a conventional VAV system does during the cooling season; however, this can be made up for by operating energy savings of 60–89% throughout the summer season.

X. Cui *et al.*, (20)	Theoretical	IEC+CCC	● Hot and Humid	Hybrid systems can reduce energy demand and consumption by pre-cooling humid outdoor fresh air with exhaust air. To this end, a computational model was built and validated against experimental data.
Chauhan and Rajput (23)	Theoretical	DEPC+CCC	● hot and moderately humid ● Hot and Dry	The suggested approach successfully reduces net monthly electricity use by 192.31 kWh in a hot, arid environment. With a 7.2-year payback period and 124.38 kWh of net monthly electricity savings in hot and humid conditions, the system can be a better option, it is concluded.
Lin *et al.*, (25)	Experimenting	Cross-flow DPEC and dehumidification	● Hot and dry ● Moderate air humidity condition	Cross-flow DPEC systems provide effective cooling when the humidity of the supply air is appropriate for the confined spaces. However, their performance suffers in humid climate conditions due to an inefficient rate of evaporation.
Baakeem *et al.*, (27)	Theoretical	DEC	● Hot and dry ● Hot and humid	It has two basic parts: (i) the creation of a theoretical model that takes into account heat and mass transmission, energy use, and cost evaluation; and (ii) its application to Riyadh, Arabia's capital, and its intense summer weather conditions. According to their findings, a direct evaporative cooler with an improved efficiency between 0.7 and 0.8 can be purchased at a reasonable price for the investigated location's summer weather.
Nada *et al.*, (28)	Theoretical	A/C and HDD System	● Hot and Dry	Based on evolution parameters for the rate of freshwater production, the refrigeration capacity of the air conditioner, electricity consumed by the air conditioner, the reduction in overall power consumptions, and the reduction in overall cost, four different proposed systems were compared to choose the best system. For units with water and energy expenses of 2.5 $/m3 and 0.02 $/(kW h), system E saves the

				most money overall as compared to golf cities, followed by system F, system C, and system D.
Chauhan and Rajput (29)	Theoretical	DEC + CCC	• Hot and Dry	The proposed system, which is based on evaporative-vapor compression, performed admirably in hot and dry conditions. From March to May, 646.8 kWh of energy savings met a minimum capacity demand. Thus, this system can become a better solution for this environment.
Tewari *et al.,* (30)	Experimenting	DEC	• Hot and dry • Hot and humid	Using the suggested mathematical relationships, the ability of DEC to mitigate heat discomfort was evaluated. Using the ASHRAE Standard 55–2013 thermal comfort zone and CCATCZ for comfort prediction, 42% and 52% of the summertime hours of thermal discomfort were avoided, respectively.
Venkateswara Rao and Datta (31)	Theoretical	DEC, IEC, DX, IEC-DEC, DEC-DX, IEC-DX and IEC-DEC-DX	• All seasons	To assess the payback duration of the proposed varied cooling modules rather than the standard DX system, a case study based on the climatic conditions of Hyderabad is done, with the predicted mean vote (PMV) kept within a range of ±2.
Abaranji *et al.,* (32)	Experimenting	DEC	• hot-dry	A cooling system based on vermicompost that operates at 2.7 m/s can achieve a cooling effect comparable to a conventional air cooler with a 10% variation. Because the pump is no longer needed, this cooling system saves roughly 21.7% of its energy.
Hussain *et al.,* (33)	Theoretical	DEC, IEC, and MEC	-	The results of this investigation show that these systems mostly rely on meteorological conditions. The examined systems and data range instead, are unaffected by system factors like area and inflow velocity.
Yan *et al.,* (34)	Theoretical	Counterflow MDEC	• hot and humid	The results showed that dead zones and the channel flow effect under the random design impaired MDEC's capacity to withstand heat and moisture.

Gupta *et al.*, (35)	Theoretical	SAC+ DEC	● hot-dry	A 68.94% increase in COP and a 26.12% and 57.23% decrease in TCR and ED, respectively, were achieved by thermo economic optimization. Particularly in hot, dry regions, DECSAC is found to notably outperform regular SAC in terms of thermo economic performance and sustainability. Depending on the operational conditions, the simple payback period of the proposed system varies from 1.21 to 2.99 years.

Refrigerant

The heat transfer medium used in air conditioning systems is called refrigerant. The performance of refrigeration systems is greatly influenced by the refrigerant used in them; therefore, it plays a crucial role, and leakage of it in the environment may result in an increase in global warming and thinning of the ozone layer. Various CFCs and HCFC refrigerants are available and are used in many industrial and domestic applications but their uses are restricted due to their high ODP and GWP. Montreal Protocol which was finalized in 1987 is an agreement to protect the ozone layer in the stratosphere. Recently, in most refrigerating systems, refrigerants R12, R22, R134a, and other azeotropic mixture refrigerants have been used as refrigerants. However, due to high toxicity, flammability, ODP, GWP, and some other causes, these refrigerants required altering with new eco-friendly refrigerants.

Numerous studies are available that provide comparisons of different refrigerants. The performance of R22 and R407C in the apparatus of a VCR system with a semi-hermetic compressor has been evaluated and it has been investigated that R22 performs better than R407C due to better compression (36). The effectiveness of seven refrigerant mixtures of propylene, propane, R152a, and dimethyl ether based, and two pure hydrocarbons, has been examined in household air conditioning and heat pumping systems and concluded that R22 can be substituted by these refrigerant mixtures (37). In air conditioning and heat pump systems, experimental studies demonstrate that R433A is a more beneficial alternative to R22 (38). Experimentally assessed the VCR system with the most recent R290/R600a refrigerant mixture to substitute the R12 and R134a from the point of view of environmental impacts i.e. ODP and GWP (39). Both R290 and R1270 refrigerants showed good performance in a 1-ton heat pump bench testing with a hermetic rotary compressor, making them suitable long-term substitutes for household air conditioners and heat pumps (40). R404A and R22 were used as working fluids in a cabinet system performance investigation, and the findings were assessed through simulation to identify the best cabinet design (41). Using a constructed computer model, an exergetic study of a real vapor compression refrigeration cycle was performed, indicating that R507A can be a more effective substitute for R502 and R404A (42). A thorough review of several experimental and theoretical literature has been done to replace the CFCs and HCFC refrigerants with new eco-friendly refrigerants (43). Experimental research has been performed on 90/10 CuNi Turbo C tubes to examine the HTCs for the outer condensation of R22 and the vapor of its retrofit equivalents R417A, R422A, and R422D (44). A theoretical analysis of traditional VCR systems using different refrigerant mixes in different ratios found that R12 can be replaced by the refrigerant mixture of R290/R600a (40/60 by wt. %) and R22 can be replaced by R290/R1270 (20/80 by wt. %) (45). An experimental inquiry has been presented to replace R134a in household refrigerators with novel refrigerants and found that for all operating conditions, R152a performs better as compared to R134a and R32 (46). The azeotropic mixture R413A has been evaluated as a direct substitute for R12 in a household refrigeration system that was designed to operate with R12; the exergetic study found that R413A consistently outperformed R12 (47). Compare the effectiveness of R404A and R507A in replacing

R502 in a double-stage compression cycle with and without the subcooler based on experimental data (48). Experimental research on a VCR unit utilizing R22 and modern HFC refrigerants including R417A, R422A, and R422D showed that no refrigerants perform better as perform R22 (49). The performance degradation of the VCR cycle was examined in terms of energy and exergy. Two sets of refrigerants were taken into consideration based on thermodynamic characteristics. While R134a from the first set showed the greatest results in every case, R717 from the second set, consistently delivered the best performance (50). R134a worked well in all settings, whereas R407C showed the lowest performance, according to a theoretical inquiry on the examination of certain refrigerants in a VCRS system (51). Experiment testing of R22, R134a, R290, and R407C in AC based on energy and exergy analysis determined that R290 performed better as compared to other refrigerants but due to its high flammability R407C can be viewed as a superior substitute for R22 (52). The performance of R1234yf and R1234ze as substitutes for R134a in a monitored VCR system, both with and without an internal heat exchanger (IHX), has been experimentally evaluated. The COP disparities between the two replacements were reduced by the installation of an IHX (53). Exergy analysis of a two-stage VCR cycle using R1234yf, R1234ze, and R134a as a working substance found thatR1234yf and R1234ze may be suitable substitutes for R134a due to their environmentally beneficial qualities (54). The CRSs for R41/R404A and R23/R404A are theoretically analyzed to determine whether R41 is an appropriate replacement for R23 or not (55). The cooling system uses the refrigerant R32 and one-phase vapor injection to help with cooling. The heat pump cycle exhibits great energy efficiency and low exit temperatures, but the refrigeration cycle performs poorly. Also, a new improved injection cycle has been proposed which consists of one and two-phase injection modes and incorporates an air conditioner that uses the R32, called IAC (56). R22 gives better performance than R407C concerning both analysis of energy and exergy. However, R410A is compatible with new design systems and R407 is a decent refrigerant from a retrofitting perspective (57). Theoretical analysis of ten binary refrigerant mixtures in different proportions by mass in 0.8 TR window air conditioner concludes that R22 can be replaced in household air conditioner applications by the mixture R1270/R290 (75/25 by mass%) because it was shown to be most similar to R22 (58). An experimental investigation concluded that while R1234ze(E) and R1234yf had greater refrigerating capacity and electrical energy consumption, respectively, the latter had a higher COP value. As a result, in terms of COP, R1234ze(E) can be used to charge vapour compression-based conditioning systems instead of R22 (59).The study investigated how two different types of flame retardants affected R1234yf's flammability. According to the findings, a comparison analysis revealed that R227ea inhibited R1234yf more potently than R134a (60). R22 can be replaced by R290 without any system retrofitting based on heat analysis and the electricity-saving abilities of the refrigerants (61). To create 600 l of hot water (40 °C) for a bath and 1200 l of chilled water (5 °C) for an IEACS, presents a model of a VCRS. The findings indicate that given the specified thermodynamic state, systems with R744, R1234yf, and R134a are 102.4%, 126.9%, and 114.2% higher than the system with R290 (62). To replace R134a in an economized-cycle VCR system, the energy and exergy analysis of the R513a investigation revealed that rebuilding or choosing a different compressor, economizer, valves, and evaporator will all increase the efficiency of the R513a system (63). The impact of nano-oil on the operation of various VCR systems presents two distinct scenarios i) VCR system operating on R134a/PAG mixture, and ii) VCR system operating on R134a/PAG/Al_2O_3 mixture. It was found that the COP improved by 6.5% as a result of the addition of nanoparticles to the system (64). A numerical model is provided for a low cooling capacity VCRS system that concentrates on the refrigerants R290, R600a, and R1234yf. According to the analysis of the thermo-economic and environmental aspects, R290 outperforms all other systems in terms of electricity consumption, efficiency, environmental protection, and economic performance (65). With evaporator temperature variation as one of the performance indicators, the behavior of R134a, R12, and R22 was evaluated using exergetic efficiency and total irreversibility. The exergetic efficiency for R12 is at its highest, followed by R22 and R134a at its lowest (66). The experimental investigation presents a nanofluid-based VCRS system and contrasts its performance with the traditional system. They concluded that in comparison to a traditional system, using 0.1 wt.% of R600a-MO-Al_2O_3 mixture enhances the COP by 37.2%, decreases electricity use by 28.7%, increases delivery pressure of compressor by 8.9%, reduces evaporator pressure by 24.7%, and shortens pull-down time by 17.6% (67). The effect of nanoparticles on the efficiency of refrigerant of the VCRS system was examined; experimental findings reveal that pure refrigerant has a lower COP than refrigerant-based nanofluid (68). An actual high-efficiency inverter room air conditioner that uses R134 as its working ingredient has been optimized using a modified exergy analysis (69). To determine the best refrigerant for the VCRS cycle, TOPSIS analysis takes into account thermophysical qualities, cost, safety, and environmental and economic issues. R513a, R134a, and R448a were found to be the best refrigerants for the system, in that order, based on how close they were to the optimal solution (70). A trial for the performance of R152a and R134a was undertaken, and their findings showed that R152a can take the place of R134a in oil-free residential refrigerators (71). Experimental research has been performed on the effect of R290/R600a on the efficiency of variable-speed hermetic compressors for residential refrigerators. It has been found that as the weight of R290 grows in the mixture, increases the mass flow rate of refrigerant, which enables higher COP (72). A novel two-stage CHB-VCRS refrigeration unit performance shows that in comparison to the other two systems, the proposed system's entire storage configuration has the biggest design capacity (73). The performance of different refrigerants such as R134a, R152a, R600a, and R290 in conventional VCR systems has been performed for condensing temperate 40°C and 45°C and evaporation temperature -30°C to 10°C. Their analysis revealed that 152a and R600a give satisfactory results (74). Using Life Cycle Climate Performance (LCCP) and TEWI methods found that R290 can become a replacement for R410A in the energy and environmental assessment of a variable-type room air conditioning system (75).

This report also emphasizes the continuous endeavors to find more environmentally acceptable alternatives to R22 refrigerant in air conditioning systems, driven by worries about global warming. Despite their widespread usage, refrigerants with high GWP, such as R407C, R410A, and R134a, are scheduled to be phased out by 2030 (76). The flammability of hydrocarbon refrigerants is a constraint, despite their low GWP and lack of ODP. As potential alternatives with low GWP and no ODP, R1234yf, and R1234ze have recently come to the forefront of research. The evolution of theoretical and experimental technologies that replace R22 in different cooling applications with new, environmentally acceptable refrigerants is shown in Table 2. Additional research is necessary to create and enhance refrigerants that meet the requirements of low GWP, zero ODP, and minimum flammability hazards. These refrigerants should be used extensively in air conditioning systems. Furthermore, further experimental validation is necessary for the practical integration of these novel refrigerants in cooling applications and different climates. The list of recent and future new environmentally benign refrigerants with low GWP and zero ODP is presented in Table 3.

Table 2: Recent Advancements to Replace R22

Authors	**Technique**	**Types of Refrigerants**	**Conclusion**	**Observations**
Dalkilic and Wongwises (45)	Theoretical	R12, R22, R134a and a blend of R134a, R152a, R32, R290, R1270, R600 and R600a in a range of ratios.	R12 and R22 can be substituted by blends of R290/R600a and R290/R1270 respectively.	The system well performs with considering the condition of superheating and under cooling.
La Rocca and Panno (49)	Experimenting	R22, R417A, R422A and R422D.	R22 performed better than other refrigerants.	New three HFC refrigerants can be used in a system without changing the

				lubricating oil and without renewing the VCRS circuit which is designed for R22.
Qureshi and Zubair (50)	Theoretical	R407C, R134a, R717, R410A, R404A and R290	From the first set of refrigerants, R134a performs better than others while from the second set of refrigerants, R717 performs better than others.	Using EES Software compared the performance of refrigerants and also found that performance degrades due to fouling.
Reddy *et al.*, (51)	Theoretical	R134a, R143a, R152a, R404A, R407C, R410A, R502 and R507A.	The system works well with R134a as compared to other refrigerants in all respects.	Using the exergetic analysis of the VCR system, compare the performance of selected refrigerants.
Padmanabhan and Palanisamy (52)	Experimenting	R22, R290, R134a, and R407C.	R290 gives better performance than other refrigerants but due to its high flammability, R407C can be considered as a replacement of R22.	This investigation compared the performance of R134a, R290, and R407C concerning factors of energy and exergy analysis and irreversibility at various locations of air conditioning units.
Yataganbaba *et al.*(54)	Theoretical	R1234yf, R1234ze and R134a	A better option to R134a might be R1234yf and R1234ze.	Exergy analysis of two evaporator VCR systems performed using (EES-V9.172-3D) software package program.
Kasera and Bhaduri (57)	Theoretical	R22 and R407C.	Despite having somewhat lower performance than R22, R407C can be the best alternative for retrofitting.	A thorough review of experiments to analyze the performance of R407C is presented.
Shaik and Babu (58)	Theoretical	Ten binary combinations of refrigerants based on R1270 and R290 by mass, along with R22.	R1270/R290 (75/25 by mass %) is a preferable substitute for R22 in residential applications because it performs similarly to R22.	Considers the actual VCRS cycle of 4/5 TR window air conditioning systems to investigate the theoretical performance of different refrigerants.
Oruç and Devecioğlu (59)	Experimenting	R22, R1234yf, and R1234ze(E).	As the COP of R1234ze(E) is better, it can become a better	Experiment test performed on a Split-type air conditioning system under four

			substitute for R22 in air conditioning refrigeration systems.	different ambient temperatures
Ajayi *et al.,* (61)	Experimenting	R22, R290, and nanolubricant/R290 mixtures.	R290 is better performed and can be substituted for R22 in the air conditioning system.	Watermelon peels from C. lanatus, a type of agricultural waste, serve to increase the refrigeration capacity of R290 and reduce cooling system energy usage by using them as nanoparticles.
Kumar *et al.,* (68)	Experimenting	R290 and nanoparticles Aluminum oxide of size 20– 30 nm size.	Compared to an R600a system, a nano refrigerant system uses less power and has a higher coefficient of performance.	Nanoparticles weighing 0.20 gm, 0.30 gm, and 0.40 gm of nano refrigerant R600a + Al2O3 were added to the system.
Ozsipahi *et al.,* (72)	Experimenting	R600a, R290/R600 (40%/60%), R290/R600 (50%/50%), R290/R600 (60%/40%), R290/R600 (70%/30%).	Based on operating conditions and the makeup of the refrigerant mixes, the COP of the refrigeration cycle is 10–20% higher than R600a.	It has been determined that adding more mass weight to the R290 mixture results in greater electricity consumption rates, it also significantly increases the mass flow rate of the refrigerant, allowing for a higher COP.
Soni *et al.,* (74)	Theoretical	R134a, R290, R600a and R152a.	R600a and R152a exhibit additional desirable qualities.	The temperature ranges for the condenser (40 ◦ C to 45 ◦ C) and evaporator (-30 ◦ C to 10 ◦ C) have been examined in this experiment.
Andrade *et al.,* (75)	Experimenting	R410A and R152a	Exergenvironmental analysis was proposed, and it proved to be very important in highlighting the benefits of R290 and the dangers posed by its	LCCP and TEWI methodologies were utilized to evaluate the energy and environmental impact of a variable-type room air conditioner.

			flammability. It also showed how some components could be designed better to increase the system's overall energy efficiency.	
Berkah Fajar *et al.,* (77)	Experimenting	410A and R290	R290 can become a better substitute to R410A Both R410A and R290 had average total exergy destruction of 524.7 W and 0.24 average exergy efficiency, respectively, and 336.1 W and 0.20 average exergy efficiency, respectively.	The experiment was conducted using a split air conditioner which was initially intended to run on R410A.

Table 3: Proposed Recent and Future Eco-friendly Refrigerants

Refrigerant	**Name**	**B.P. (℃)**	**C. P. (℃)**	**ODP**	**GWP**	**Safety Group**
R404A	R125/R143a/R134a	-47	73	0	3800	A1/A1
R422A	R125/ R134a/R600a	-46.5	71.75	0	3,143	A1
R417B	R125/R134a/ R600	-44.9/-41.5	89.89	0	3027	A1
R422D	R125/R134a/R600a	-45.8	79.56	0	2,729	A1
R427A	R32/R125/R143a/R134a	-43.2	85.3	0	2,138	A1
R417A	R125/R134a/R600	-41.2	89.89	0	2346	A1
R438A	R32/R125/R134a/R600/R601a	-42.33	85.27	0	2,265	A1
R410A	R32/R125	-51	72	0	2000	A1/A1
R407C	R32/R125/R134a	-44	87	0	1700	A1/A1
R32	Difluoromethane	-51.7	78.2	0	550	A2L
R152a	1,1-Difluoroethane	-24.0	113.3	0	120	A2
R290	Propane	-42	97	0	20	A3
R432A	R1270/R170	-46.6	97.3	0	1.64	A3
R433A	R1270/290	-44.6	94.4	0	2.85	A3
R513A	R-1234yf/134a (56%/44%)	-29.4	96.5	0	573	A1
R600	Butane	0	152.01	0	4	A3
R600a	Isobutane	-11.7	134.7	0	4	A3
R717	Ammonia	-33	133	0	0	B2L
R1234yf (New)	2,3,3,3-Tetrafluoropropene	−29.45	94.7	0	4	A2L
R1234ze(E) (New)	trans-1,3,3,3-Tetrafluoroprop-1-ene	-18.97	109.36	0	6	A2L

Energy Statistics

Due to the rapid expansion of the global economy and the development of new technologies, global energy consumption is becoming more and more in demand. Energy technology obscurities, insufficient primary energy resources, and negative repercussions like global warming, climate change, ozone layer depletion, etc. received more attention as a result of the explosive rise in the energy sector. To give everyone a comprehensive understanding of energy systems and markets, the IEA produces a wide variety of datasets, from which Key World Energy Statistics (KWES) highlights the most important facts and trends. Apart from data on particular fuels and energy balances, KWES includes information on energy transitions, including prices, CO2 emissions, energy security, efficiency, and public RD and D spending. The geographic coverage is wide, encompassing statistics on the entire "IEA family" and beyond, in keeping with the "Open Doors" policy of IEA. The International Energy Agency (76) reports that over the past 20 years (1995-2015), there has been an increase in primary energy use. In 2020, there was a 4% decrease in the world's energy demand. Although this is the highest absolute reduction and decline since World War II, the energy demand globally is expected to rise by 4.6% in 2021. The International Energy Organization predicted that the whole global CO2 emissions from fuel burning in years of 2019 would be 33622Mt, as illustrated in Figure 1. Figure 2 shows the overall final energy consumption by sources for the year 2019 as reported by the Organization for Economic Co-operation and Development. Figure 3 depicted the global final energy consumption as being 418EJ across all sources and regions. Figure 4 illustrates the ultimate energy consumption of coal, oil, natural gas, and electricity by sector. Figure 5 depicts the total final energy consumption by sector was calculated as 515848pj and 390390pj for stated policies and sustainable development, respectively for the scenario of 2040. CO_2 emissions by region were calculated as 33274 Mt and 14704 Mt for stated policies and sustainable development, respectively for the scenario of 2040 that has been shown in Figure 6.

Figure 1: World CO2 Emissions from Fuel Combustion (A) by Sources (B) by Region (76)

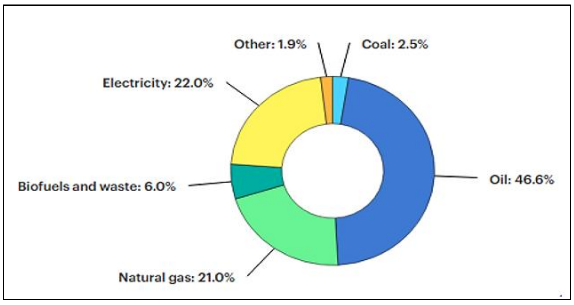

Figure 2: OECD Total Final Energy Consumption by Sources (76)

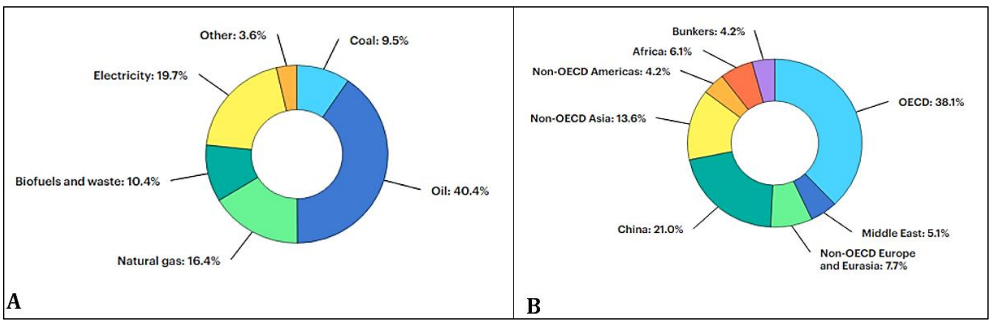

Figure 3: World Total Final Energy Consumption (A) by Sources (B) by Region (76)

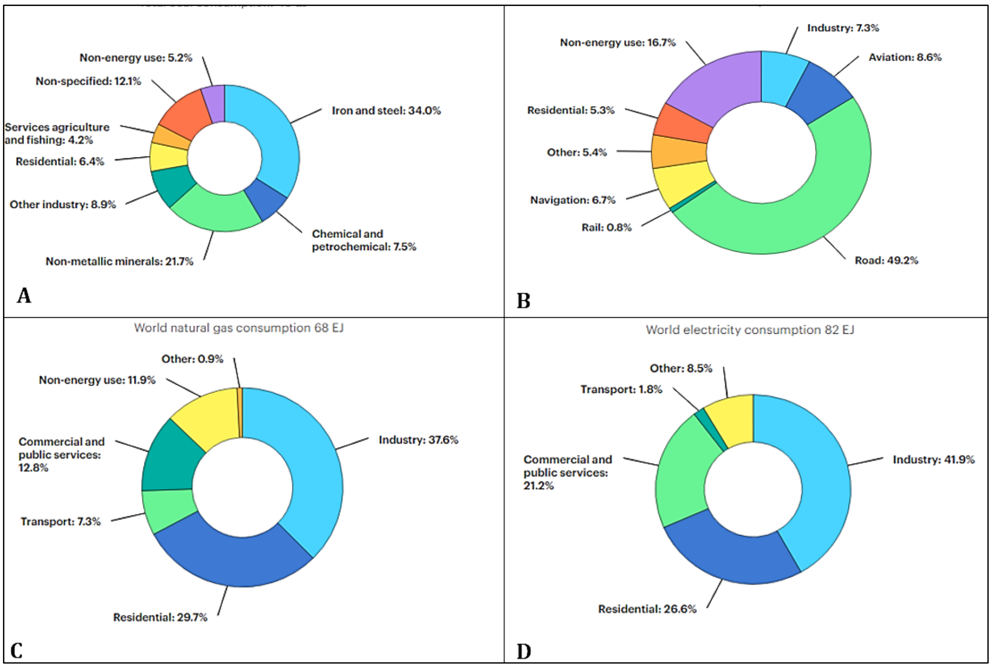

Figure 4: Final Consumption From (A) Coal (B) Oil (C) Natural Gas and, (D) Electricity by Sector (76)

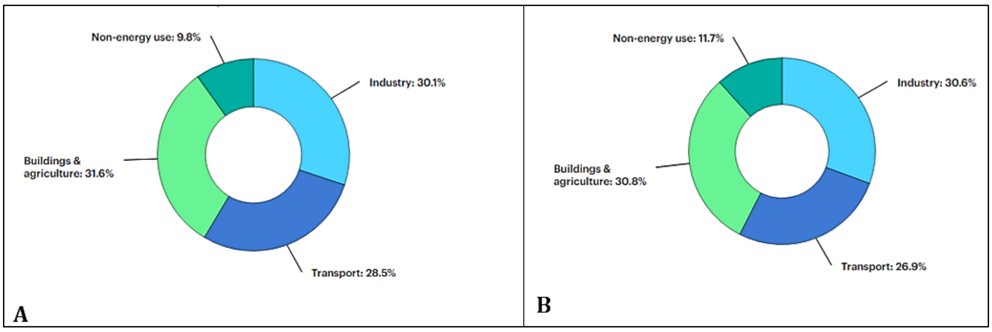

Figure 5: Total Final Consumption by Sector (A) in the Stated Policies (B) in the Sustainable Development in Scenario 2040 (76)

Figure 6: CO2 Emissions by Region (A) in the Stated Policies (B) in the Sustainable Development in Scenario 2040 (76)

Discussion

Experimental Setup

Various types of cooling systems with different capacities are available on the market which are used for human comfort. Figure 7 depicts the working principle of DE and IE cooling systems respectively. After improving the working of these cooling systems new cycle was proposed as M-cycle and Wet and dry cross-flow heat exchanger in M-cycle shown in Figure 8, 9 respectively. The water-spraying evaporative equipment for passively cooling buildings is shown in Figure 10. A Direct Evaporative Cooler (DEC) and a traditional air conditioner are coupled in this study to satisfy the cooling requirements of a climate-controlled space. As depicted in Figure 11, the evaporative cooler and air conditioning system work together as a single device. Using a DEC with an air conditioner is not particularly straightforward; some modifications are required to combine these units. Direct evaporative coolers are placed in front of the evaporator cooling coil and these two devices are connected with a duct to carry the outdoor 100% fresh air from the direct evaporative cooler to the cooling coil of A/C. After, passing through the cooling coils, the ducting system carries the dehumidified and cooled air into the conditioned area. To reduce the temperature of condenser coils, conditioned air from the room is used with the help of a condenser fan. Measuring instruments like anemometer, pressure gauges, and temperature sensors are placed at the required location of the modified combined system. After the climate-controlled space has reached a steady state; cooling load estimation is carried out. Table 4 provides details of the specifications and components of the experimental setup, while Table 5 presents the instruments used in the combined system (24). The combined system operates in three modes (I, II, III) depending on the climatic conditions, with a provision for comparison. The working conditions for each mode are detailed in Table 6.

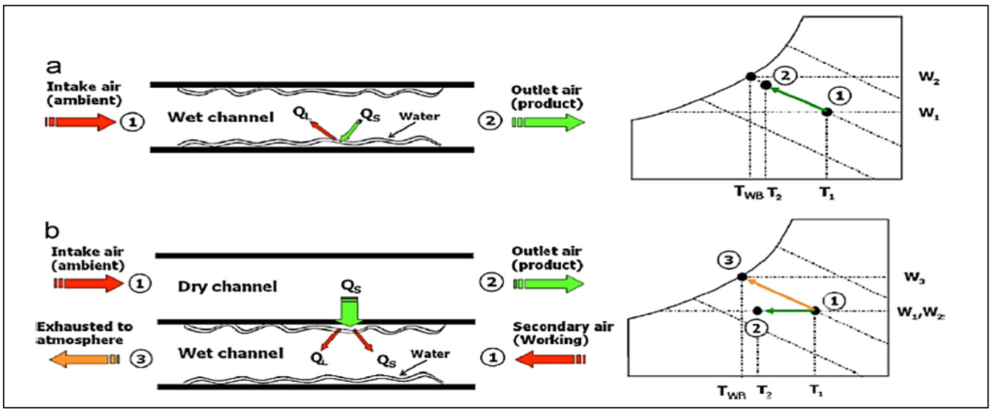

Figure 7: (A) Direct Evaporative Cooling and Indirect Cooling and (B) Indirect Evaporative Cooling (22)

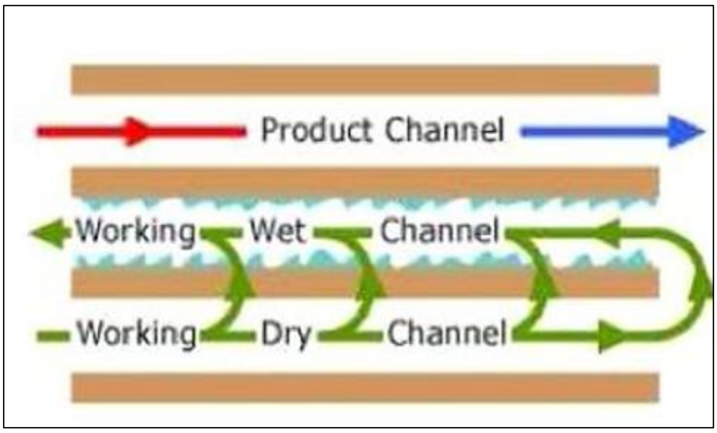

Figure 8: Working of M-Cycle (22)

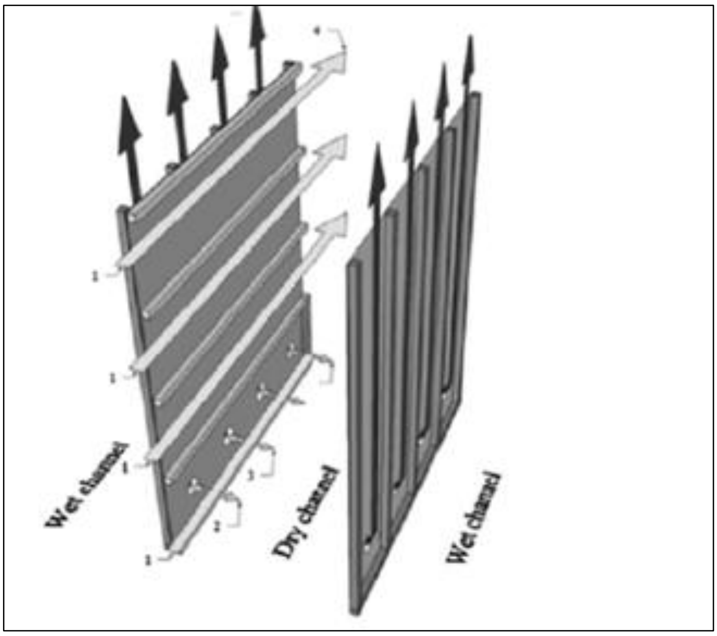

Figure 9: Wet and Dry Cross-Flow Heat Exchanger in M-Cycle (22)

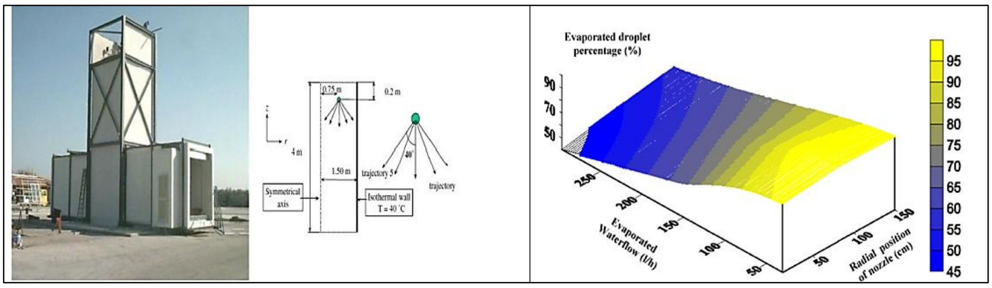

Figure 10: Water Spraying Evaporative Unit for Passive Cooling of Buildings (22)

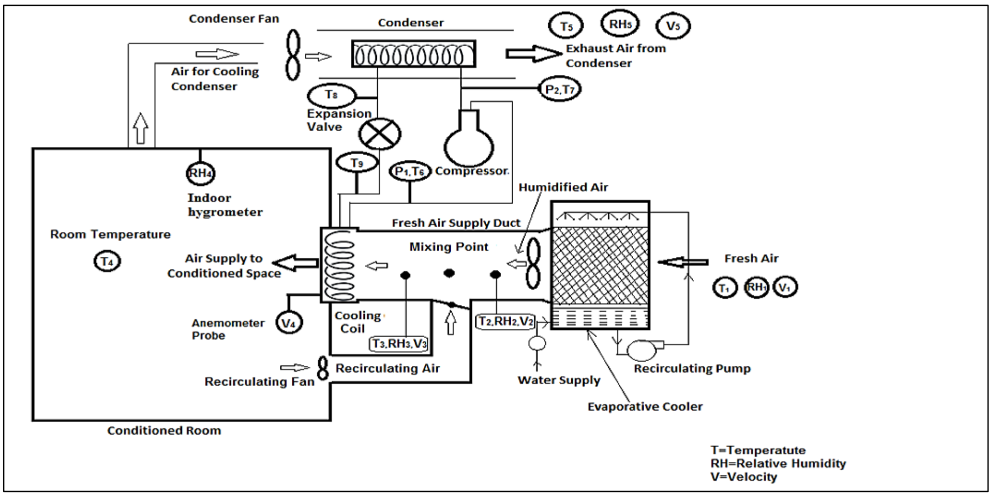

Figure 11: Combined System of Conventional Air Conditioning System Along with Direct Evaporative Cooler

Table 4: Specifications and Components of the Experimental Setup (24)

Components	Dimensions/Type	Quantity/Material
Evaporator	44 cm x 40 cm	Copper tube
Condenser	56 cm x 41 cm air cooled	Copper tube
Compressor	Reciprocating type	Hermetic 1800 W
Evaporative Cooler	61 cm x 74 cm x 112 cm	22 SWG (0.7 mm) GI Sheet
Evaporative Cooler tank	20 cm x 66 cm x 84 cm	22 SWG (0.7 mm) GI Sheet

Refrigerant	New eco-friendly refrigerant	950 g
Cooling capacity of VCACS	COP: 3	6.5 kW
Fresh air duct cross section	46 cm x 46 cm	0.5 mm Aluminium sheet
Recalculating air duct cross-section	30 cm x 30 cm	0.5 mm Aluminium sheet
Evaporative cooler pad material	Three pads	Aspen Wood
Evaporative cooler Fan	Four blade exhaust fan	200 W
Exhaust air Fan for condenser	Four blade exhaust fan	200 W
Recalculating air Fan	Four blade exhaust fan	200 W
Evaporative cooler pump	Submersible type	30 W
Conditioned Room	10 m x 10 m x 10 m	1 Room

Table 5: Presents the Instruments Used in the System (24)

Equipment Type	Make	Range
Hot wire anemometer	Lutron digital instruments	0.2-20.0 m/s 0°C-50°C DBT
Probe type thermo-hygrometer	Lutron digital instruments	10%-95% R.H 0°C-50°C DBT
Indoor thermo-hygrometer	Mextech	10%-95% R.H 0°C-50°C DBT
16-20 channel temperature data logger	Sunpro Instruments	10,000 data can be store
T- type thermocouple wire	Sunpro Instruments	-50°C -250°C
Probe type thermo-hygrometer	HTC (HD-304)	-30°C -100°C 0%-100% RH
Energy Meter	HPL	0.1-10,000 kWh

Table 6: Modes of Operation for Different Weather Conditions

Modes of Operation	Weather	T_d (*in*°C)	T_w (*in*°C)	Observations
I	Moderate Hot and Dry	T_d<34°C	T_w<23°C	Only DEC can work efficiently with 100% fresh air
II	Hot and arid	T_d>34°C	20°C<T_w<23°C	Both direct evaporative cooler (DEC) and compressor (A/C) can work efficiently
III	Humid condition	T_d>34°C	T_w>34°C	Only the compressor (A/C) can work efficiently with 100% fresh air

System Configuration

The purpose of this research is to provide a solution for the cooling requirements of a climate-controlled space by combining a traditional air conditioner with a Direct Evaporative Cooler (DEC). The cooling load and energy savings may be assessed by mathematical modeling of the system.

Evaporative Cooling Unit (DEC):

- The DEC lowers air temperatures by evaporation, which keeps the enthalpy constant.
- Equation [1] is used to simulate the DEC's outlet air temperature: $T_{ec} = [T_0 - \left\{\left(\frac{\varepsilon}{100}\right) \times (T_0 - T_{w0}\right)\} [1]$

Air Conditioning Unit:

- After passing through the DEC, the air is cooled even more in the air conditioner to achieve the desired temperature and humidity.
- Equation [2] is used to describe the air temperature at the intake of the restricted zone (combined system): $T_{cs1} = [T_{c1} + \{BPF \times (T_{ec} - T_{c1})\}]$ [2]

Conventional Air Conditioning System:

- Instead of using the DEC process as a middleman, the traditional approach cools the air directly. With the help of equation [3], we can determine the air temperature at the entrance of the restricted area: $T_{cs2} = [T_{c1} + \{BPF \times (T_{ec} - T_{c1})\}]$ [3]

Estimating Cooling Loads Using Energy Equations:

A mathematical model is developed to represent the energy equations for a DEC and AC system that operates in tandem. To calculate the cooling load for a climate-controlled room, one uses these equations, which are based on a number of research and publications (14, 24, 69, 78, 79).

Enthalpy of Air through DEC:

- The enthalpy remains constant across the DEC:

$h_0 = h_{ec}$ [4]

- For the combined system, enthalpy at the inlet of confined region is given by equation [5]:

$h_{s1} = [h_{c1} + \{BPF \times (h_{ec} - h_{c1})][5]$

- For the conventional system, enthalpy at the inlet of confined region is given by equation [6]:

$h_{s2} = [h_{c2} + \{BPF \times (h_{ec} - h_{c2})\}]$ [6]

Cooling Load Calculation:

- Combined System: Cooling load on the cooling coil:

$Q_{c1} = m_a \times (h_{ec} - h_{s1})$ [7]

- Conventional System: Cooling load on the cooling coil:

$Q_{c2} = m_a \times (h_{ec} - h_{s2})$ [8]

Sensible Cooling Rate:

- Combined system:

$Q_{scr1} = m_a \times (1.005 + \omega_{s1} \times 1.88) \times (T_{cs1} - T_i)$ [9]

- Conventional system:

$Q_{scr2} = m_a \times (1.005 + \omega_{s2} \times 1.88) \times (T_{cs2} - T_i)$ [10]

Energy Savings:

- The percentage reduction in cooling load on the cooling coil is expressed as:

Saving in $Q_c(\%) = \{\frac{Q_{c2} - Q_{c1}}{Q_{c2}}\} \times 100$ [11]

Air temperature and humidity are measured at key locations, such as the DEC outflow and the coil input, as part of the measuring methodologies utilized in this study. To ensure a more accurate outcome, mass flow meters are used to calibrate the airflow rates. Data analysis methods utilized in this study are based on these measures. To analyse the experimental data and find the cooling loads and performance metrics of the system, energy equations are used. Additionally, Equation 11 is used to compare the energy savings of the conventional and combined systems by calculating the percentage reduction in cooling demand. The combined system's performance may be evaluated across three modes using these methodologies, as noted earlier. Experiment replication is assured by the precise approach, which demonstrates the efficacy of combining an air conditioner with a Direct Evaporative Cooler (DEC) for efficient cooling.

Conclusion

In this study, we look at three critical challenges that need immediate attention: i) reducing the health risks associated with air conditioning systems that do not have enough humidity; ii) finding new environmentally friendly refrigerants to replace old, harmful ones like R22, R134a, R407C, etc.; iii) find ways to make cooling systems more efficient and cost-effective than they already are.

Reducing the health risks associated with air conditioning systems that do not have enough humidity: according to the literature analysis, extended exposure to dry air from air conditioners can cause dehydration and respiratory conditions including bronchitis and asthma. Furthermore, joint discomfort brought on by dehydrated synovial fluids is becoming a major issue, especially for people of all ages. Controlling indoor humidity levels with a mix of air conditioning systems and evaporative coolers (DEC) has shown potential in addressing these health issues. Energy-saving advantages have been shown for this integrated system, which functions well in hot, dry, and humid environments as well as in moderately hot, arid ones (23, 29). At 43.3°C and 18.1% humidity, the system specifically saves 43.3% of its total energy use. The technology functions effectively at break-even levels in humid environments. With monthly savings of 58.5 kWh in moderately hot and arid conditions and 163.5 kWh in hot and arid climates, the system provides notable energy savings (24). Direct and indirect evaporative cooling systems, along with traditional air conditioners, are discussed in this article, along with their uses in different climates and applications for human comfort. The health dangers of using air conditioning for lengthy periods can be reduced, however, by using a hybrid system that incorporates both traditional AC and direct evaporative cooling. Although this combined approach works well in hot, dry climates, it has difficulties when exposed to higher humidity. The long-term effects of air conditioning on human health, especially in areas where humidity levels are very variable, require more investigation. Furthermore, there has been little research on how well hybrid cooling systems work in humid environments. Table 1 presents a thorough analysis of the development and results of cooling systems adapted to various regions. For hybrid systems to be successfully implemented in real-world settings, it is essential to address practical obstacles such as space constraints, installation complexity, maintenance demands, and user acceptability. More discussion of possible solutions to these problems is required.

Findings new environmentally friendly refrigerants to replace old, harmful ones like R22, R134a, R407C, etc.: Because present refrigerants have high GWP and ODP values, the second difficulty is the immediate need to replace them with ecologically acceptable alternatives. Harmful refrigerants include R22, R134a, and R407C. By January 1, 2025, refrigerants with GWP values of more than 750 must have been phased out (76). New refrigerants, such as R1234yf and R1234ze(E), can be used for immediate replacement in systems like air conditioning split systems, however, POE oils may be needed for retrofitting existing systems. To demonstrate the progress achieved in this field, Table 2 offers a thorough literature evaluation centered on R22 replacement with new, eco-friendly refrigerants. Table 3 meanwhile provides a selected collection of known and to-be-examined refrigerants, showcasing their potential for use in future cooling systems. However, many practical concerns need to be resolved before these novel refrigerants can be successfully used in the real world. These concerns include the need for storage space, the complexity of the installation, the continuous maintenance requirements, and the acceptance of the modifications by the users. To guarantee a seamless shift to more environmentally friendly refrigerants, it is important to investigate potential solutions to these problems.

Find ways to make cooling systems more efficient and cost-effective than they already are: Growing energy consumption in the construction industry, especially in cooling technologies, makes it all the more vital to improve cooling system efficiency and cost-effectiveness. According to the International Energy Agency (IEA), there will be a significant increase in worldwide energy use by 2040. This underscores the critical need for creative solutions to decrease energy prices, boost efficiency, and decrease emissions of greenhouse gases. Several innovative cooling technologies have emerged as potential replacements for conventional air conditioning, according to research. These include new dew point evaporative cooling systems, direct and indirect evaporative, wet and dry, cross flow heat exchangers in M-cycle, and combined systems of evaporative cooler and air conditioning systems have been described. In hot, dry areas, these systems, especially evaporative cooling, are more cost-effective and work better (22). They improve performance across different climatic zones and increase the coefficient of performance (COP) when combined with solid or liquid desiccant devices. Space constraints, installation complexity, maintenance demands, and user acceptance are some of the obstacles that must be overcome before these technologies can be scaled up for practical usage. The key to achieving broad acceptance is finding ways to overcome these challenges. While both conventional air conditioning and direct evaporative cooling (DEC) with 100% fresh air are useful in hot and dry climates that are moderately hot, DEC is particularly effective in these areas. On the other hand, when it comes to humid settings, only air conditioning systems can consistently offer fresh air. The practical hurdles of implementing these technologies must be overcome for them to be deployed on a broad scale across varied climates, notwithstanding the considerable promise they represent.

Abbreviations

h_s: air enthalpy/kg (in kJ/kg),ε: effectiveness of evaporative cooler,m_a: air mass flow rate (in kg/s),Q: Estimation of cooling load (in kW),Q_r: refrigeration rate of conditioning space (in kW),Φ: relative humidity (in %),ω: Humidity/kg air (in kg/kg of dry air),T: temperature (in°C),BPF: cooling coil's bypass factor, scr: sensible cooling rate, S: Supply, EC: evaporative cooler, O: ambient condition, CS: conditioned space, C: cooling coil,1: combined system, 2: conventional system, COP: coefficient of performance, DEC: dew point evaporative cooler, CCC: conventional cooling coil, IEC: indirect evaporative cooler, TR: tons of refrigeration, HDD: humidification dehumidificat-ion desalination, ADP: apparatus dew point temperature (in °C),T_{dp}: dew point temperature (in °C),T_w: wet bulb temperature (in °C),T_d: dry bulb temperature (in °C),VCRS: vapour compression refrigeration system, B.P.: boiling point, C.P.: critical point, S. G: Safety Group.

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Author Contributions

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Conflict of Interest

The authors declare that they have no competing interests.

Ethics Approval

Not applicable.

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