

Review

Review of Evaporative Cooling Systems for Buildings in Hot and Dry Climates

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Abstract: Evaporative cooling systems have gained increasing attention as an energy-efficient solution for climate control in hot and dry regions. This review aims to assess the effectiveness of the most recent advancements in evaporative cooling technologies for building applications in hot and dry climates. The review focuses on global literature, with an emphasis on building applications. The findings of this review indicate that evaporative cooling systems with hybrid configurations, particularly multi-stage systems, can achieve cooling efficiencies of up to 95%. These systems are highly energy-efficient, with energy consumption ranging from 0.3 to 1.2 kW/t, with hybrid and multi-stage designs showing the best performance. Direct and indirect evaporative cooling systems also perform well, with cooling effectiveness ranging from 60% to 85%. Their reliance on water, rather than harmful refrigerants, results in minimal environmental impact, making them an eco-friendly alternative to traditional cooling methods. The coefficient of performance (COP) for these systems is favorable, with hybrid and multi-stage designs reaching COP values as high as 35, indicating substantial cooling output relative to energy input. In addition, the performance of evaporative cooling systems is highly influenced by their design parameters and operating conditions. Advanced designs that incorporate multi-stage cooling and effective water management tend to provide enhanced cooling capacity and energy efficiency. Therefore, evaporative cooling systems are an excellent option for sustainable building practices, contributing significantly to energy savings and reduced environmental impact.

Keywords: building; evaporative cooling system; hybrid; effectiveness; hot–dry climate



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1. Introduction

The world's energy crisis has been getting worse every day, affecting households, companies, and entire economies everywhere. The high cost of fuel, of which natural gas accounts for more than half, is responsible for 90% of the increase in the average cost of producing electricity globally [1]. Price and economic pressure are major barriers to people accessing modern electricity [1].

The world is currently very concerned about the rapid depletion of energy supplies and the significant emissions of greenhouse gases that cause climate change. In some regions, extreme heat waves and droughts are becoming more common [2]. Because of the increase in global warming, building cooling load has also increased dramatically. As a result, using an air conditioning system is essential for maintaining the building's internal thermal comfort. However, the majority of heating, ventilation, and air conditioning (HVAC) systems consume a lot of electricity.

In Sub-Saharan Africa, 43% of the people do not yet have access to electricity [3]. Despite having about 18% of the world's population, Africa uses less than 6% of the

energy produced worldwide [3]. In Ethiopia, a country in Sub-Saharan Africa, only 45% of people have access to electricity [4]. As of 2019, the country's urban and rural areas are, respectively, 75% and 14% electrified [5]. Furthermore, almost 96% of Ethiopians do not have access to clean cooking technology or fuels [6]. Ethiopia nevertheless has a large potential for renewable energy because of its 45 GW of hydropower, 10 GW of wind, 5 GW of geothermal, and 4.5–7.5 kWh/m²/day of sun irradiation ranges [7].

It is difficult for underdeveloped nations like Ethiopia to use conventional air conditioning (HVAC) systems due to limited access to electricity and the high upfront and operational costs associated with these systems. To tackle this problem in developing countries, energy-efficient technology and solutions for both new and old buildings must be given top priority. An evaporative cooling system is one energy-efficient technique that works well in a variety of climates [8]. Furthermore, a solar-powered evaporative cooling system could also be a useful way to address the lack of electricity in underdeveloped nations like Ethiopia, which have abundant solar energy. Evaporative cooling systems work better than air conditioning, typically in hot-dry climates [9]. Evaporative cooling is widely used in both residential and commercial buildings, particularly in hot-dry areas like the Middle East, the Southwestern United States, Australia, the Indian subcontinent, Northern Mexico, Northwest China, and Eastern Africa [10].

Evaporative cooling systems can be broadly classified into two categories: direct and indirect. Direct evaporative cooling (DEC), which is frequently applied to home systems, lowers the air's moisture content by evaporating water [11]. For indirect evaporative cooling (IEC), the supply air was passively cooled by passing over a medium before entering the space. Therefore, unlike DEC systems, moisture is not supplied to the supply air stream. For the best performance, IEC systems were always combined with direct evaporative cooling systems or other cooling mechanisms; this configuration is known as a hybrid evaporative cooling system [12]. The comparison of the performance (COP) of an evaporative cooling system is about 15–20, which is higher than other refrigeration cooling techniques [13]. Table 1 displays the COP values for thermoelectric, evaporative, vapor compression, and vapor absorption cooling systems.

Table 1. COP value for some air conditioning systems [9].

System Type	Vapor Compression Cooling	Vapor Absorption Cooling	Thermoelectric Cooling	Evaporative Cooling
COP	2.0–4.0	0.60–1.20	0.20–1.20	15.0–20.0

Despite the promising potential of evaporative cooling systems in addressing the energy crisis and enhancing thermal comfort in hot and dry climates, several significant gaps in the current literature remain. First, while there is substantial research on the performance of evaporative cooling technologies, there is a limited exploration of their integration with renewable energy sources, as well as a scarcity of research on the application of evaporative cooling systems in building contexts within underdeveloped regions like Ethiopia. Existing studies often overlook the unique challenges faced in these contexts, such as cultural factors and infrastructure limitations. Additionally, the feasibility of implementing these systems in both rural and urban areas of Eastern Ethiopia has not been addressed, resulting in a gap in understanding how these technologies can be effectively adopted and scaled. Furthermore, while the existing literature discusses the technical aspects of evaporative cooling, there is a need for more interdisciplinary research that encompasses environmental, economic, and social dimensions. This gap presents an opportunity for future studies to contribute to a more holistic understanding of how evaporative cooling can mitigate energy challenges and enhance access to cooling solutions in underdeveloped regions like Ethiopia.

The objective of this review is to assess the most current advancements in evaporative cooling technologies, which have the potential to be environmentally friendly, energy-efficient, and capable of providing adequate thermal comfort in hot and dry climates.

Therefore, numerous research approaches suitable for building applications were considered. Research articles indexed in Scopus, Web of Science, PubMed, Google Scholar, etc., have been considered in this review study.

2. Thermal Comfort and Climate Condition in Ethiopia

Human thermal comfort is characterized as a mood that expresses contentment with the surroundings. High temperatures, along with elevated humidity, can cause pain and, in certain cases, heat stress. Furthermore, heat stress and pain cause workers to be less productive and can even cause more serious health issues, particularly in older workers [14].

The human body feels comfortable when a proper combination of air temperature, relative humidity, and motion of air is present in the occupied space. Between 22 and 27 degrees Celsius and between forty to sixty percent relative humidity, humans often feel comfortable [15]. The environment becomes hostile when the relative humidity falls below or rises over the specified range. Therefore, it is important to use cooling mechanisms to keep humans comfortable in hot and dry climate conditions.

Climate zones are categorized using the Köppen climate classification method, which divides climates into five main groups based on seasonal patterns of temperature and precipitation. Tropical is represented by A, dry by B, temperate by C, continental by D, and polar by E [16]. Figure 1 clearly indicates that the Köppen climate classification primarily categorizes the eastern region of Ethiopia as exhibiting Warm Semi-Arid (BSH) and Warm Desert (BWh) climates [16]. The eastern part of Ethiopia is more widely referred to as a hot and dry climate.

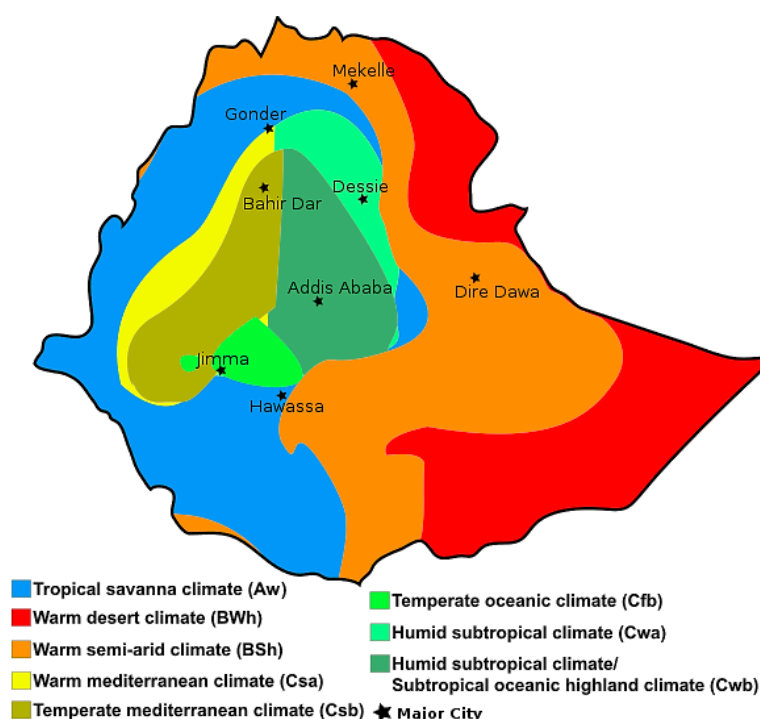


Figure 1. The Köppen–Geiger climate classification in Ethiopia [16].

In Eastern Ethiopia, temperatures can vary significantly based on altitude and proximity to the Ethiopian Highlands [17]. Average daily temperatures in the lowland areas typically range from 25 °C to 35 °C (77 °F to 95 °F) [18]. The hottest months are generally from March to May, where temperatures can occasionally exceed 40 °C (104 °F) in the hottest lowland areas, creating challenging conditions for both human habitation and agricultural practices [19]. Relative humidity in Eastern Ethiopia is equally variable, with average values often ranging from 20% to 40% in the lowland semi-arid regions [20]. During the wet season, which typically spans from June to September, relative humidity can increase.

However, the overall aridity of the region persists, leading to dry conditions for much of the year, which significantly influences the local climate and agriculture [21]. The relationship between high temperatures, low relative humidity, and seasonal variations underscores the importance of utilizing adaptive cooling solutions, such as evaporative cooling systems, to enhance thermal comfort in both residential and agricultural settings [22].

3. Introduction to Evaporative Cooling Systems

An evaporative cooling system is broadly categorized as direct, indirect, and combined/hybrid evaporative cooling. When using an IEC system, there is no moisture addition to the area as there is with a direct system. Direct and indirect evaporative cooling systems, as well as any other cooling mechanism like hybrid systems, are used to provide heat rejection and lower water and energy usage.

Evaporative cooling systems (ECS) keep indoor temperatures within a comfortable range of 23–27 °C and maintain humidity levels between 30 and 50%, making them well-suited for ensuring occupant comfort [23]. Moreover, ECS has demonstrated significant energy efficiency, cutting energy consumption by 30–40% compared to conventional air conditioning systems [23]. This makes ECS a sustainable option for improving comfort and reducing energy usage in buildings located in hot, dry climates [23].

The thermodynamic processes involved in evaporative cooling systems, including heat and mass transfer mechanisms and their applications in building cooling, focusing on factors like wet-bulb temperature and adiabatic processes that influence air conditioning performance. Wet-bulb temperature is a critical parameter influencing the performance of ECS, impacting the cooling capacity and overall efficiency [24]. The adiabatic process contributes to energy savings and sustainability in air conditioning applications [24]. Evaporative cooling systems (both DEC and IEC) are more energy-efficient and environmentally friendly compared to conventional cooling systems, making them ideal for sustainable applications, especially in hot and dry climates.

4. Advantage and Disadvantage of Evaporative Cooling vs. Conventional Cooling

Evaporative cooling systems (both DEC and IEC) are more energy-efficient and environmentally friendly compared to conventional cooling systems, making them ideal for sustainable applications, especially in hot and dry climates. Unlike conventional cooling systems, which typically rely on mechanical refrigeration, evaporative cooling systems offer numerous advantages, including reduced energy consumption and lower environmental impact. However, they also present certain limitations, especially in terms of performance in humid conditions and humidity control. The advantages and disadvantages of evaporative cooling systems versus conventional cooling systems are presented in Table 2. This comparison highlights the advantages and disadvantages of both evaporative cooling systems and conventional cooling systems, examining key factors such as energy efficiency, environmental impact, initial costs, and suitability for different climates.

Table 2. Comparison of evaporative cooling systems and conventional cooling systems: advantages and disadvantages.

Criteria	Evaporative Cooling Systems	Conventional Cooling Systems
Energy Efficiency	✓ Highly energy-efficient, often reducing energy consumption by up to 75%.	✓ Generally, less energy-efficient, leading to higher energy bills.
	✓ Lower operational costs.	✓ Increased energy consumption, especially during peak seasons.

Table 2. Cont.

Criteria	Evaporative Cooling Systems	Conventional Cooling Systems
Environmental Impact	✓ Lower carbon footprint due to minimal refrigerant use. ✓ Reduced environmental harm.	✓ Higher carbon footprint from significant refrigerant use, contributing to ozone depletion and global warming.
Cooling Performance	✓ Effective in hot, dry climates, providing significant cooling. ✓ Performance can diminish in high humidity.	✓ Consistent cooling performance across various climates, including humid conditions.
Initial Cost	✓ Lower initial installation costs with simpler designs.	✓ Higher initial costs due to complex machinery and installation requirements.
Humidity Control	✓ Increases indoor humidity, which may not be ideal for all environments.	✓ Excellent humidity control, maintaining comfortable indoor conditions.
Maintenance Requirements	✓ Requires regular maintenance to prevent mold and bacteria buildup; generally simpler to maintain.	✓ Routine maintenance required, often needing professional servicing for complex systems.
Suitability for Climate	✓ Best suited for hot, dry climates; performance declines in humid conditions.	✓ Versatile and effective in a wide range of climates, including humid and arid environments.
Design Flexibility	✓ Simple and adaptable design, can integrate with existing systems.	✓ Fixed design, less adaptable to specific environmental needs.

5. Thermodynamics of Evaporative Cooling

The working principle behind evaporative cooling is the thermodynamics of water evaporation or the transformation of water from a liquid phase into a vapor. The evaporation process is endothermic since it involves a phase shift that demands energy. This energy, which comes from the internal energy of water, is known as the latent heat of vaporization. Therefore, throughout the process, the air and the water both cool.

Since there is typically very little heat exchange between the airstream and its surroundings, evaporative cooling is best described as an adiabatic process. On the psychrometric chart, the evaporative cooling process thus follows a line of constant wet-bulb temperature. Since the lines for constant enthalpy and wet bulb temperature in the psychrometric figure nearly overlap, it is also possible to assume that the enthalpy of the airstream will remain constant ($H \cong \text{constant}$) [25]. Air cooling calculations frequently employ this approximation since it is reasonably precise.

$$T_{wb} \cong \text{Constant} \quad (1)$$

$$H \cong \text{Constant} \quad (2)$$

The humidity in the air can be determined using the dew point temperature [26]. The dew point can be found by decreasing the surface temperature to a point where water starts to condense. Dew point can then be determined by taking a surface temperature measurement [26].

The temperature decrease achieved is one of the most crucial data points for evaluating the performance of evaporative cooling systems. By measuring the difference between the DBT at the inlet (T_{in}) and outlet (T_{out}), or the saturation effectiveness (ϵ), it can be determined the maximum temperature decrease that can be obtained in an adiabatic process. Saturation effectiveness can be expressed as the variation between the ambient air's DBT (T_{in}) and WBT ($T_{wb,in}$) [27]. The amount of moisture that the media may evaporatively

release into the air is what is meant by the term “Cooling Efficiency”, which is another name for saturation effectiveness. And can be computed by applying Equation (3).

$$\varepsilon = \frac{T_{in} - T_{out}}{T_{in} - T_{wb,in}} \quad (3)$$

Cooling capacity (CC) is another helpful metric to describe cooling performance. The ability of the system to cool a certain airstream is better described by this parameter [27].

$$CC = \dot{m}_a \cdot C_{pa} \cdot (T_{in} - T_{out}) \quad (4)$$

where: \dot{m}_a is air mass flow rate in $\frac{kg}{s}$, and C_{pa} is the specific heat of air in $\frac{J}{kg \cdot K}$.

To assess the energy consumption rate of air handling equipment by industry, the energy efficiency ratio (EER) was established [28]. The energy efficiency ratio is expressed as the amount of thermal energy taken from the air for cooling purposes over watt of energy used.

$$E_{ER} = \frac{\Delta H}{P} = \frac{\text{Cooling Capacity}}{\text{Power consumed}} \quad (5)$$

where: ΔH is change in enthalpy across the cooling pad and P is the electrical power input for the exhaust fan and water pump in kW [28].

The coefficient of performance (COP) of an evaporative cooling system quantifies its efficiency by comparing the cooling effect produced to the energy input required to achieve that effect. It is a crucial metric for assessing how effectively an evaporative cooling system operates [29]. The formula for calculating the COP of an evaporative cooling system is as follows:

$$COP_{\text{evaporative}} = \frac{Q_c}{W} \quad (6)$$

where: Q_c is cooling capacity in kilowatts, W is power input (energy consumed) in kilowatts

Evaporative cooling systems, when represented on a psychrometric chart, demonstrate how temperature and humidity levels in the air are manipulated to achieve cooling. Direct evaporative cooling (DEC) involves the process of cooling air by adding moisture, resulting in a reduction of the dry-bulb temperature and an increase in relative humidity. This process follows a line of constant wet-bulb temperature, showing a horizontal movement to the left on the psychrometric chart [30]. Indirect evaporative cooling (IEC), on the other hand, cools air without adding moisture. It lowers the dry-bulb temperature but keeps the humidity level constant, resulting in a downward-left movement on the chart [31].

Hybrid evaporative cooling combines both direct and indirect cooling processes. Air is initially cooled without adding moisture through indirect cooling and then further cooled with moisture addition via direct cooling. This combination produces a more substantial temperature drop. These processes are visually mapped on the psychrometric chart, showcasing how evaporative cooling systems provide an energy-efficient method for cooling, particularly in dry climates [31]. The psychrometric chart effectively illustrates the interaction between temperature, moisture content, and relative humidity, making evaporative cooling a sustainable alternative to conventional air conditioning.

6. Classification of Evaporative Cooling Technology

Evaporative cooling system is broadly categorized as direct, indirect, and combined/hybrid evaporative cooling. Direct evaporative cooling systems are classified as active and passive depending on their driven mechanism and whether they are power-consuming or not. Indirect evaporative cooling systems are also classified as wet-bulb and sub-wet bulb systems depending on the heat exchange mechanism between the primary and secondary working fluid. The combined/hybrid evaporative cooling system is further classified as two-stage, three-stage, and multi-stage hybrid evaporative cooling system based on its working principle. Figure 2 illustrates the classification of evaporative cooling systems.

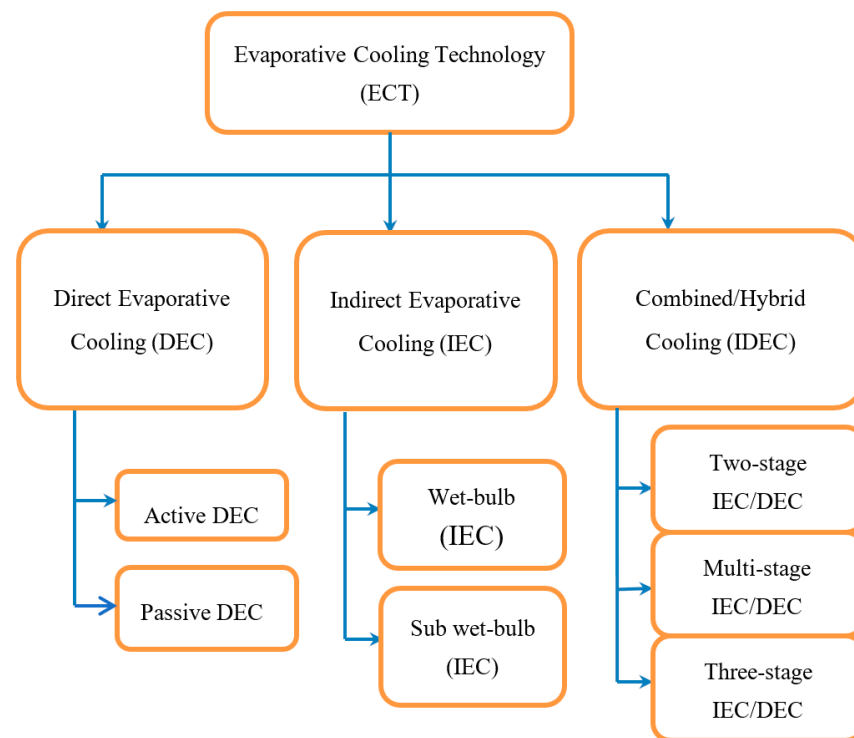


Figure 2. The general classification of evaporative cooling systems.

7. Review of Evaporative Cooling System by Type

Evaporative cooling systems have gained widespread attention as a sustainable alternative to conventional mechanical cooling methods, particularly in regions where energy efficiency and environmental concerns are paramount. The effectiveness of an evaporative cooling system is closely tied to its design, operational principles, and the specific climate in which it is employed. Over the years, various types of evaporative cooling systems have been developed, each offering unique advantages and limitations in terms of cooling performance, energy consumption, and applicability to hot and dry weather conditions.

This section reviews the major classifications of evaporative cooling systems—direct, indirect, and hybrid systems—highlighting key studies that have explored their efficiency, energy consumption, water consumption, and practical implementation to hot and dry weather conditions. By categorizing the systems in this way, we aim to provide a clearer understanding of how each type functions and the specific advantages and challenges it faces, especially in hot and dry climates.

7.1. Direct Evaporative Cooling (DEC)

The most basic and conventional kind of evaporative cooling is direct systems, where water and outdoor air come into direct contact. The technique is just cooling air by converting a form of energy (sensible energy into latent energy). For hot and dry areas, direct evaporation cooling systems are appropriate. Relative humidity can rise to 80% in damp situations. Because of the potential for warping, corrosion, and mildew in sensitive materials, a direct supply of such high humidity into the building is not recommended [9]. DEC systems can be further subdivided into two categories: passive DEC, which are naturally operated, and active DEC, which run on electricity [9]. The active direct evaporative cooling systems are propelled by electrical systems for water and air circulation. However, when compared to vapor compression systems, active direct ECS are considered less energy-intensive systems with the possibility of saving up to 90% in energy [13].

Energy is not needed for the passive direct ECS to operate and utilize natural phenomena. Nevertheless, they might need pumps or fans with a modest capacity. The climate has

an impact on this kind of system. This kind of device is said to be able to lower interior air temperatures by roughly 9 °C [32]. Figure 3 shows the schematic diagram for DEC systems.

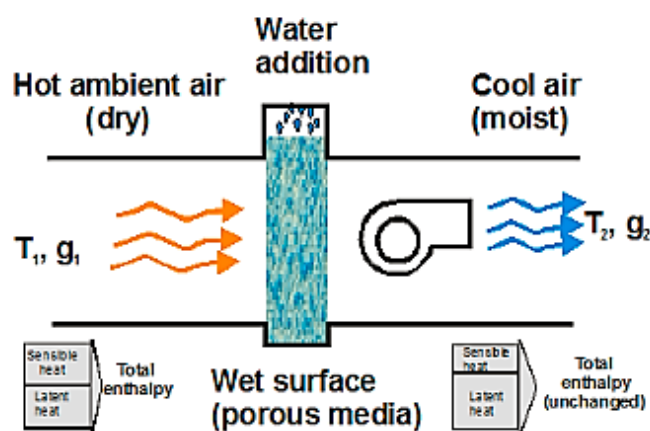


Figure 3. DEC systems schematic diagram [33].

For arid as well as semi-arid climates, direct evaporative cooling can be taken as an energy-effective air conditioning alternative [34]. The materials and construction qualities of commercialized evaporative cooling pads differ. The velocity of air, pad thickness, pad geometry and layout, and water flow rate are the most researched factors of evaporative cooling pad operation [34]. Typical performance indicators of the pad include its saturation effectiveness, temperature drop, the treated air's increased humidity, water evaporation and consumption, and cooling capacity [34].

Temperature variation and air relative humidity have a significant effect on the efficiency of evaporative cooling techniques compared with different roof heat gain-reducing techniques [35]. There are positive results when evaporative cooling systems are used in arid areas like BSk and BWh, but the benefits are modest in humid equatorial climates [35].

Dogramac [36] experimentally determined the performance of five new natural porous materials to see how well they performed when used for DEC systems in hot and dry areas. The materials consist of Cyprus Marble (CM), Ceramic Pipes (CP), Dry Bulrush Basket (DBB), Yellow Stone (YS), and Eucalyptus Fibers (EF) [36]. EF and CP were identified as the most potential candidates, with efficacy values ranging from 72% to 33% and 68% to 26%, cooling capacity varying between 0.13 kW and 0.71 kW, and 0.12 kW to 0.55 kW, with air velocities ranging from 0.1 to 1.2 m/s. YS was also considered a competitive material, with effectiveness and cooling capacity falling within the range of 46% to 22% and 0.08 kW to 0.48 kW, respectively, for similar air velocities.

Using experimental research, the effectiveness of direct evaporative cooling systems with and without dehumidifying pads was assessed and compared [37]. The suggested system's maximum ability to cool, efficiency, and coefficient of performance (COP) without the dehumidifying pad were 3.84 kW, 84.6 percent, and 16.1, respectively. Comparable values with the system operating with a dehumidifying pad were 3.2 kW, 71.4 percent, and 13.4 [37]. More water can evaporate into the surrounding air due to the decreased relative humidity, which leads to increased water usage. The total amount of water used on the experimental day was 8.93 L, resulting in an average daily water consumption of 0.99 L/h when the system is not equipped with a dehumidifying pad [37]. An average of 1.08 L/h water consumption was recorded during the experimental day when the suggested system was combined with a dehumidifying pad, for a total daily water usage of 9.73 L [37].

Two commonly used parameters for assessing the effectiveness of evaporative cooling pads are saturation efficiency and pressure drop [38]. According to A. Tejero-Gonzalez [38], future studies should take into account the impact of additional variables on the cooling efficiency of the DEC system, such as power requirement, water utilization, material decay, air quality, and the influence of water temperature and salinity.

Meyer [39] examines the effectiveness of direct evaporative coolers (DEC) in various climatic conditions through mathematical modeling. The research highlights that in hot and dry climates, DEC systems achieve significant cooling efficiency, with temperature reductions exceeding 10 °C [39]. However, in humid environments, their performance declines sharply, often resulting in temperature drops of less than 5 °C due to reduced evaporation rates [39]. The study also identifies critical factors influencing DEC performance, including air temperature, relative humidity, and the difference between wet-bulb and dry-bulb temperatures. The authors emphasize the necessity of choosing the right climatic conditions for DEC implementation, indicating that hot and dry regions are optimal for achieving the best energy savings and cooling efficiency.

Reddy [40] designs and investigates performance analysis of direct evaporative cooling (DEC) systems in hot and dry climates. The study identifies a number of important variables that affect DEC system performance, including airflow rate, cooling efficiency, and saturation efficiency. The result shows that, depending on the operational and design aspects, the cooling effectiveness varied from 60% to 90% [40]. A temperature reduction of up to 12 °C was accomplished by DEC systems in extremely hot and dry conditions, and performance improved significantly as the ambient air temperature increased [40]. A number of variables, including pad material, thickness, and airflow rate, affected saturation efficiency, which ranged from 70% to 85%. Higher airflow rates were shown to increase water consumption; however, the study recommended design improvements to balance cooling efficiency and water consumption. Depending on the system design and conditions, the water consumption per square meter of the cooling pad surface ranged from 5 to 10 L/h [40]. This demonstrates that DEC is appropriate for arid, hot conditions.

Siripurapu [41] explores the use of bio-inspired cooling techniques for building envelopes, particularly in hot climates. The approach mimics evapotranspiration in trees, integrating passive cooling methods to improve thermal comfort and energy efficiency. The system employs double-skin facades, utilizing water flow and natural ventilation through an aerofoil-like structure on the building's exterior. The simulation result shows that such facades can lower the temperature by 2–5 °C compared to buildings without this feature [41]. This passive system contributes to energy savings and reduces the carbon footprint, especially in mixed-mode operations that combine passive and mechanical cooling. A case study was also performed for a commercial complex in Raipur; the building's annual energy performance index (EPI) was reduced from 86.8 to 80.3 kWh/m² through the integration of this cooling method [41]. The study emphasizes the significance of designing building envelopes that can leverage natural cooling methods, thus reducing reliance on mechanical cooling systems

7.2. Indirect Evaporative Cooling (IEC)

A significant benefit of IEC systems over DEC systems is the previous one uses a method of cooling air by reducing sensible heat without altering its humidity. A standard IEC system consists of a tiny fan, a heat exchanger, a pump, a water tank, and a water distribution line [9]. Figure 4 shows the typical diagram of an IEC system. The two common indirect evaporative cooling systems are wet-bulb temperature and sub-wet bulb (dew-point) temperature evaporative cooling systems [9].

Ahmed [42] utilizes mathematical optimization to investigate the performance of indirect evaporative cooling (IEC) systems in building environments. This study focuses on how different parameters affect these systems' performance, such as humidity distribution, air velocity, and the size of the water spray unit. According to the optimization result, based on the particular building environment and climate conditions, changing the water spray unit size by 10–20% can increase cooling effectiveness by 15% [42]. Furthermore, a 10–12% increase in cooling effectiveness is obtained by increasing air velocity by 20–30%, particularly in larger rooms [42]. To provide more uniform cooling throughout the building, optimizing humidity distribution can raise thermal comfort by 5–8% [42]. The findings

show that it is possible to greatly improve the cooling performance of the IEC system by modifying certain important parameters [42].

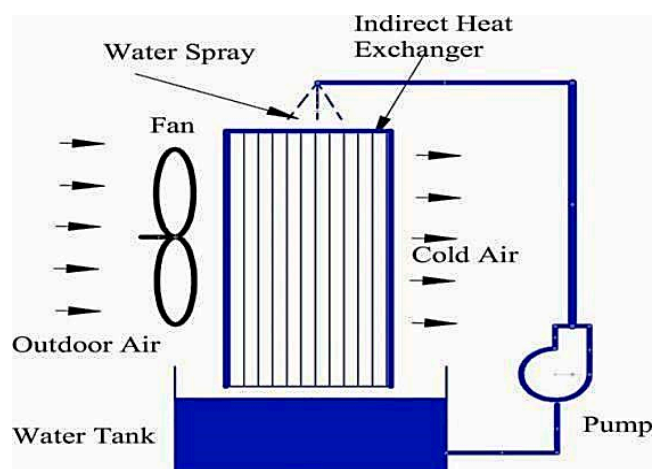


Figure 4. Schematic diagram of IEC system [13].

Lai [43] investigates the effectiveness of indirect evaporative cooling systems (IECs) across various climatic conditions by integrating solid desiccants through numerical methods. This study particularly emphasizes their performance in hot, dry environments, where traditional cooling methods may be less effective. According to the results, in typical Australian climates, the system can handle air conditions with a supply air temperature below 19 °C and a humidity ratio below 11.51 g/kg [43]. In these areas, the solid desiccant-assisted system shows significant promise since the desiccants assist in controlling humidity levels, which improves the efficiency of the evaporative process [43].

Liu [44] optimizes a heat and mass transfer model for energy recovery in indirect evaporative cooling systems. The study aims to enhance the annual energy efficiency of these systems by analyzing various operational parameters and their impacts on cooling performance. The result shows that the annual energy efficiency ratio (EER) for the energy recovery indirect evaporative cooling system could achieve values exceeding 10.5, which demonstrates significant improvement compared to conventional systems [44]. The system's energy consumption was reduced by approximately 30–40% compared to traditional cooling methods, particularly in regions with high humidity [44]. The study reported optimized heat transfer coefficients ranging between 15 to 30 W/m²·K, depending on the specific operating conditions and environmental factors [44]. The energy efficiency of indirect evaporative cooling systems can be considerably increased by optimizing the heat and mass transfer model, which emphasizes the significance of incorporating energy recovery mechanisms to improve overall cooling performance in a variety of climatic conditions [44].

7.2.1. Wet-Bulb Temperature IEC

Heat exchange takes place via a heat-conductive plate in wet-bulb temperature IEC systems between primary and secondary operating fluids. Thus, no extra moisture is added to the cooled air supply stream; the supply air is only subjected to sensible cooling. In contrast, the latent heat of vaporization is the mechanism via which heat is transferred between the working air and the water in wet channels [45–47]. Figure 5 shows the schematic structure and working principles of a typical wet-bulb temperature IEC system.

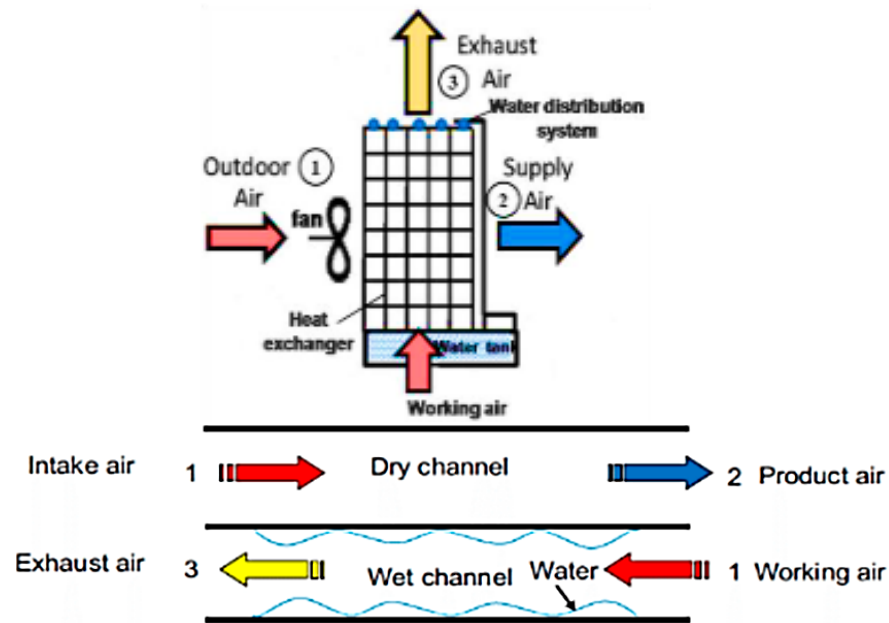


Figure 5. Schematic structure and working principles of wet bulb temperature IEC [9].

7.2.2. Sub-Wet-Bulb Temperature IEC

Recent research has focused on lowering air temperatures below the ambient air wet-bulb temperature to enhance the indirect evaporative cooling system's cooling capacity [48].

The sub-wet-bulb temperature IEC system is also known as Maisotsenko cycle (M-cycle). This system combines evaporative cooling with a cross-flow multi-perforated flat plate heat exchanger. As illustrated in Figure 6, the secondary air must be pre-cooled in the dry channel before being redirected to pass through the wet channel. Consequently, the primary air temperature is lower than the wet-bulb temperature and is closer to the entering air's dew point temperature [9]. As compared to conventional heat exchangers, the M-cycle heat exchanger is 10–30% more effective [49].

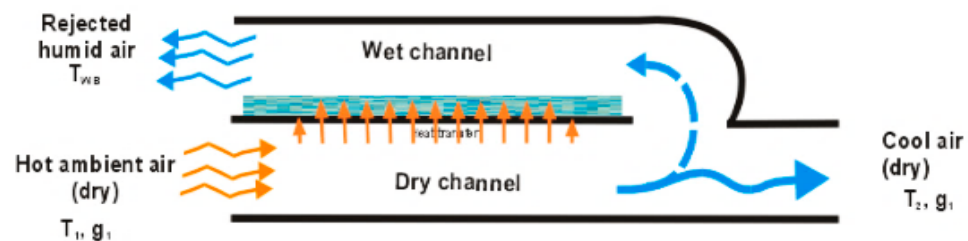


Figure 6. Schematic diagram of sub-wet-bulb temperature IEC [33].

Sajjad [50] examined the performance of advanced IEC systems, comprising Maisotsenko cycle coolers, dew point coolers, regenerative IECs, and conventional indirect evaporative coolers. According to this review work, evaporative material, air passage geometry, inlet air flow situation, and the system's configuration are essential factors to consider when designing an IEC system for greater efficiency and cooling capacity [50]. In the future, IEC systems may replace the conventional cooling systems used in buildings and other applications [50].

A parametric study was carried out to determine the performance of a cross-flow IEC using computational fluid dynamics [51]. According to this study, the humidity and temperature distribution of the suggested 3D model improved by 5.8% and 6.7%, respectively, as compared to a 2D model [51].

Sun [52] analyzed the performance of new material on a tubular porous ceramic IEC using theoretical and experimental methods. A number of structural and operational

factors were taken into account when doing the performance analysis, including the working/output air volume ratio, wall thickness, wet-bulb temperature reduction, and tube length and spacing. In conclusion, as compared to other parameters, the tube length significantly affects the cooling efficiency of IEC [52].

Experimental analysis in real climate conditions was carried out on dew point IEC, which comprises a heat and mass exchanger built from a locally accessible polymer material, to see how effective it is [53]. The result shows that the performance of the dew point IEC system increases with the increase in the ambient temperature and decreases with the increase in the relative humidity of air [53]. The author suggests the proposed system can be used for residential cooling purposes [53].

The effectiveness of regeneration indirect evaporative cooling (RIEC) systems under variable inlet air conditions was examined using experimental and mathematical modeling [54]. The dew point effectiveness in this investigation is 0.91, indicating a considerable degree of cooling was accomplished [54]. The proposed system is also recommended for use as a model to examine the overall global behavior of RIEC [54].

The performance of combined/hybrid cooling systems (IEC systems in combination with other cooling mechanisms) was examined experimentally for application in hot-dry areas [55]. The outcomes indicate that the combination of IEC with thermal insulation and nocturnal radiative cooling had better cooling potential as compared to other possible combinations [55].

A new regenerative evaporative cooler performance was assessed using a mathematical model and experiment conducted under a carefully controlled laboratory environment [56]. The experimental result shows that the system is suitable for arid climates under typical ambient conditions because the temperature of the cooled air supplied was 14 °C less than the ambient air [56].

Parametric analysis was carried out to evaluate the effect of working air ratio, inlet temperature, and air passage length on the design of a dew point cooler [57]. The proposed system was designed for application in French and Algerian climate conditions. According to this study, dew point coolers can supply air at a temperature below that of the ambient wet-bulb temperature [57]. The result of this study shows that there is a strong agreement between the simulated results and the experimental results in the literature review [57].

Experimental research was completed to investigate the effectiveness of indirect evaporative cooling systems for application in hot and dry areas [58]. The wet medium is made of porous/fired clay, and the working and supply air is arranged in counter-flowing channels [58]. The result of this study demonstrates that the IEC would accomplish overall wet bulb effectiveness more than unity and a cooling capacity of about 27 W/m². Because of its performance, the system could be used in place of building air cooling units [58].

The effectiveness of a sub-wet-bulb temperature IEC system was determined using computer modeling and validated with experiment tests to apply for building space cooling [59]. The result indicates that the proposed system may be able to replace conventional mechanical air conditioning systems in buildings in hot-dry areas [59].

7.2.3. Evaporative Roof Cooling System

A roof evaporative cooling system is a passive cooling method that utilizes the evaporation of water on or near the roof surface to lower the temperature of the building. The system works indirectly, as the evaporative process happens on the exterior, and no moisture is added to the indoor air. Roof evaporative cooling is especially effective in hot climates [60].

The purpose of an evaporative roof cooling system is to lower the temperature of a roof within a specific range. In this system, the building's roof is utilized to expel heat. Heat is extracted from the building through water evaporation in evaporative roof cooling systems [61].

Roof cooling is one of the green cooling technologies that can be constructed by applying an optimal water spray system and cooling water installation in direct evapo-

rative cooling systems [62]. The domes' diameter and the cooling channel's dimensions considerably impact the thermal efficiency of passive DEC systems with domed roofs [62].

Sakdawattananon [63] studied numerically the performance of uncovered roof ponds, which is a type of passive IEC system with and without water flow. This research determines the impact of ambient temperature, solar radiation, and constant water evaporation on the thermal performance of uncovered roof ponds. The results indicated that an uncovered roof pond with a water depth of 0.2 m effectively prevented heat flow into the building. Additionally, a roof pond with water flow ranging from 0.1 to 0.4 m was able to remove heat from the roof through water circulation [63].

The effectiveness of an IEC and rooftop sprinkler was determined with respect to temperature reduction and capacity of cooling [64]. According to the modeling results, the indirect evaporative cooler lowers the inside temperature by 9.2 °C. However, the temperature is only lowered by 4.4 °C by the rooftop sprinkler system [64].

The cooling potential of an IEC system and a roof pond with wet fabric membranes and floating fiber (gunny bags) was experimentally tested in various actual environmental conditions and compared to each other to create an effective building model [65]. In hot-humid climates, the performance of all proposed systems is similar. But in hot-humid areas, the wet fabric device performs better in terms of thermal efficiency than other IEC systems [65].

Sharifi [66] studied the effectiveness of roof pond cooling mechanisms for heating and cooling buildings. In comparison to other types of roof pond cooling systems, the study indicated that roof ponds with wet gunny bags, shaded roof ponds, vented roof ponds, and roof ponds with movable insulation were more successful [66]. Furthermore, the author's investigation revealed that the primary factors influencing the efficacy of roof ponds were weather, water depth, roof deck material, and insulating panel thickness [66].

These days, a variety of roof cooling systems are available, such as roof ponds, cool-painted roofs, insulated roofs, double roofs, air ventilation systems. . . etc. The schematic representation of the evaporative roof cooling system is illustrated in Figure 7.

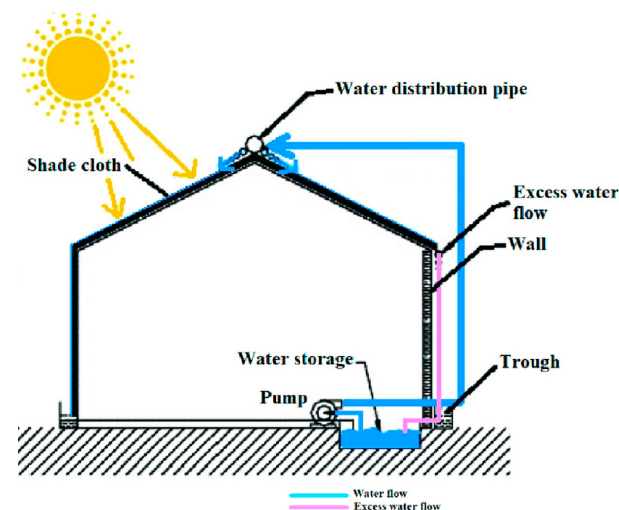


Figure 7. Schematic diagram of evaporative roof cooling system [67].

7.3. Combined/Hybrid/Evaporative Cooling System

Hybrid evaporative cooling systems integrate both IEC and DEC methods. DEC is highly effective but raises indoor humidity levels, whereas IEC is less effective but maintains constant humidity in the supplied air. Combining these two systems, or even integrating them with other cooling technologies, can achieve a blend of their respective advantages. This integrated approach is commonly referred to as a hybrid ECS [13]. The effectiveness of hybrid evaporative cooling systems ranges between 90% and 115% [13]. However, the complexity of the system and its high initial cost are the main advantages [19].

There are two common types of combined systems: two-stage IDEC, three-stage IDEC, and multi-stage IDEC.

7.3.1. Two-Stage IDEC

The two-stage evaporative cooling system produces colder air compared to the single-stage system working alone. Due to its ability to maintain an ideal range of indoor humidity, the two-stage systems often offer more comfort than conventional systems [9]. In an advanced two-stage evaporative cooler, a variable-speed blower circulates cool air using 100% outside air. Two-stage evaporative coolers can save energy usage by 60–75 percent compared to conventional air conditioning systems [68]. Figure 8 illustrates the schematic diagram of the two-stage IDEC system.

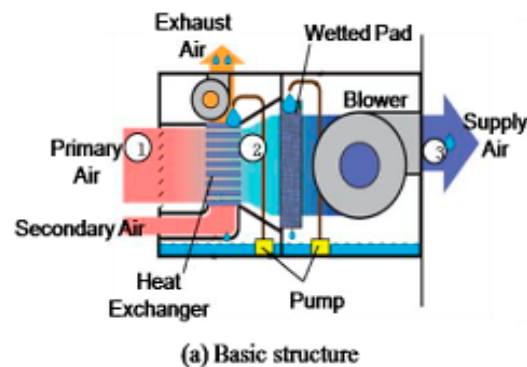


Figure 8. Schematic structure of two-stage IDEC (1: Primary air, 2: Pre-cooled air, 3: Supply air) [6].

7.3.2. Three-Stage IDEC

Three-stage IDEC systems consist of a two-stage IDEC system in combination with a cooling cycle. An IEC and/or DEC, together with a solid desiccant dehumidification system, can achieve a COP of around 20 [9]. By combining an IEC and a DEC together with a desiccant dehumidification system that provides sensible and adiabatic cooling, the system can be capable of achieving energy savings of 54–82% over conventional cooling systems [9]. Figure 9 illustrates the schematic diagram of solid desiccant and evaporative cooling systems.

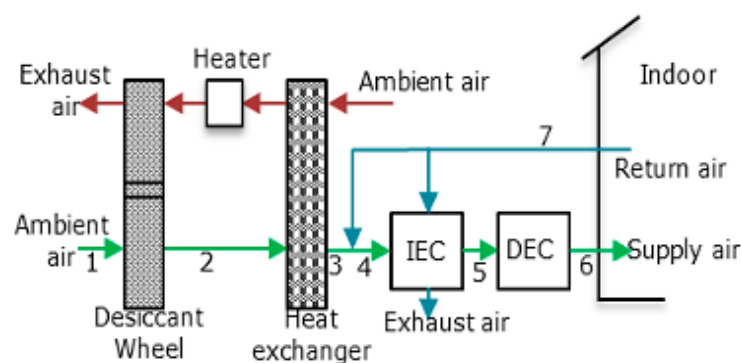


Figure 9. Schematic of solid desiccant and evaporative cooling systems [9].

7.3.3. Multi-Stage IDEC

Multi-stage IDEC is a combined system of a two-stage IDEC and multiple cooling cycles, as shown in Figure 10a. For example, a system that combines a two-stage IDEC system with nocturnal radiative cooling. A cooling coil of Multi-stage IDEC is more effective than two-stage evaporative cooling systems. The energy-saving capacity of this system ranges from 75 to 79% compared to mechanical vapor compression (MVC) systems [9]. Figure 10b illustrates the hybrid system of radiative cooling, cooling coil, and two-stage IDEC system.

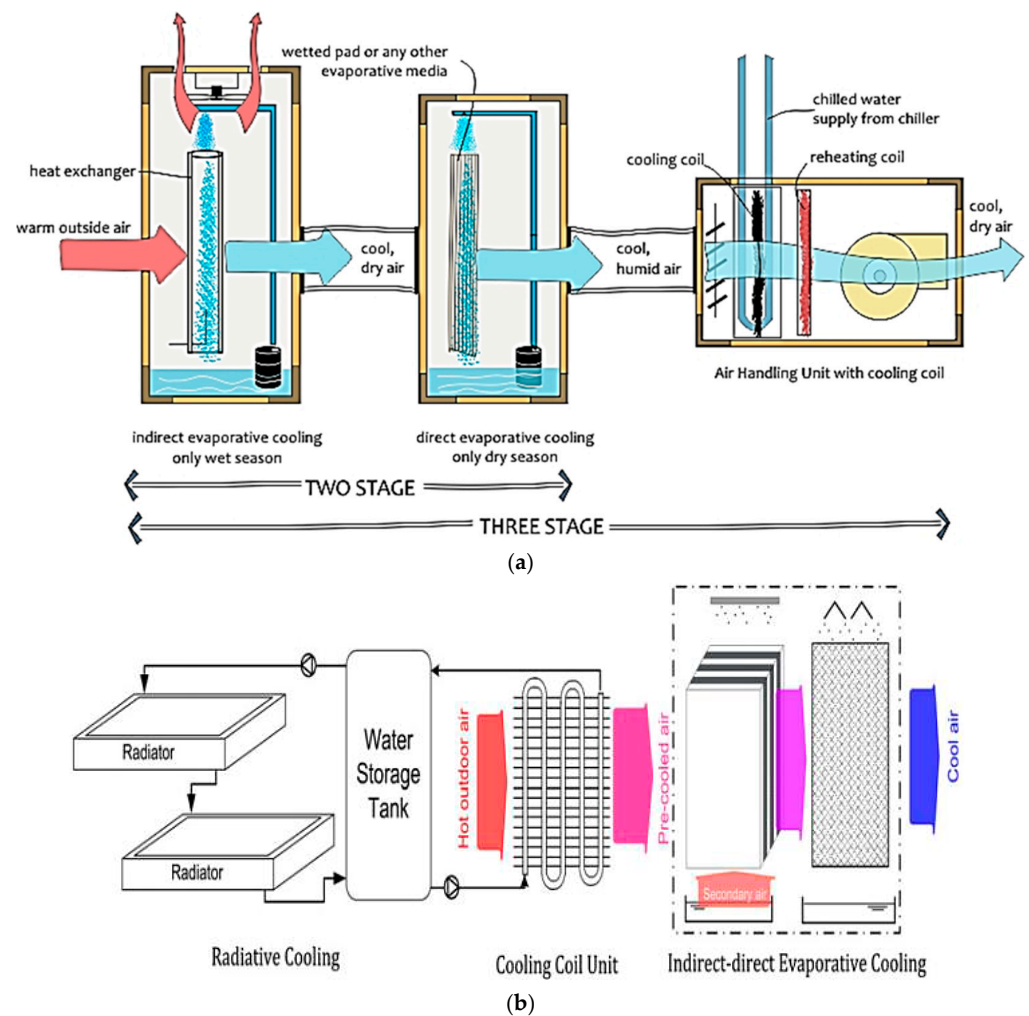


Figure 10. (a) Schematic diagram of a multi-stage evaporative cooling system [69]. (b) Hybrid system of radiative cooling, cooling coil, and two-stage IDEC system [9].

Chen [70] reviewed the most recent research on the hybrid IEC-MVC system and compared its efficiency with a standalone MVC cooling system. In addition, the paper explains the potential of this hybrid system for long-term energy savings under particular climate conditions. Furthermore, the author discussed the water consumption and economic feasibility of the proposed hybrid system [70]. Water consumption poses a significant challenge in arid regions experiencing severe water scarcity. The typical method to decrease water usage is by recovering the condensate from the mechanical vapor compression unit [70].

Theoretically evaluate the efficiency and water usage of a new hybrid system, which combines an IEC with an underground air tunnel [71]. The plan for the future involves replacing the vapor compression cooling cycle with this innovative hybrid system [71]. The proposed system's cooling performance is evaluated using the finite difference full implicit method [71]. The simulation results of this study indicate the cooling efficiency is improved and the water consumption is highly reduced by connecting the underground heat exchanger to an IE cooler [71].

The performance of IEC systems integrated with the latent heat thermal energy storage (LHTES) is determined using thermodynamics analysis [72]. The modeling results show that the studied hybrid system can simultaneously dehumidify and pre-cool the ambient air in tropical regions. The surrounding air temperature can be lowered by 6–10 °C, and the humidity ratio is also reduced by 2–11 g/kg of dry air within specific operating ranges [72].

The combined effectiveness of an M-cycle counter-flow heat exchanger and a solar-assisted desiccant dehumidifier was conducted experimentally [73]. The solar collector

efficiency and solar fraction of the hybrid solar thermal collector design were examined. The technological, economic, environmental, and climatic benefits of solar thermal systems combined with other renewable energy-dependent cooling techniques were discussed [73]. After evaluation, the suggested hybrid system's maximum cooling capacity is determined to be 4.6 kW [73].

Shekh [74] reviewed advancements in evaporative cooling systems, specifically focusing on how their integration with air dehumidification methods can enhance performance in hot and humid climates. The review indicates that incorporating methods like desiccant and membrane dehumidification can lead to a significant increase in cooling efficiency, even under humid conditions [74]. It also notes that employing independent dehumidification before the cooling process, particularly with membrane systems, proves to be more energy-efficient than traditional methods. This hybrid approach shows promise as a viable alternative to vapor compression systems, which are generally less environmentally friendly [74]. This study underlines the potential of these enhanced cooling solutions to reduce energy consumption while enhancing thermal comfort in challenging climates.

Mohamed [75] analyzed the performance and potential of combining evaporative cooling (EC) with solar energy (SE) for sustainable building cooling, emphasizing the development of mathematical models to optimize energy usage and cooling efficiency. The review shows that direct evaporative cooling (DEC) systems can achieve energy reductions of up to 90% under specific conditions compared to conventional mechanical vapor compression (MVC) systems [75]. In terms of cooling efficiency, dew-point evaporative cooling (DPEC) configurations, particularly the Maisotsenko cycle (M-cycle), outperform traditional methods by achieving lower air temperatures, sometimes reaching dew-point levels [75]. The proposed hybrid systems also showed promising results in terms of exergoeconomic performance, which evaluates both the energy efficiency and the cost-effectiveness of the cooling processes [75]. These results generally indicate that hybrid EC-SE systems are a feasible choice for effective and sustainable building cooling, especially in hot and dry regions.

8. Summary of Performance Metrics for Evaporative Cooling System

Evaporative cooling systems (ECS) have developed as an efficient and sustainable solution for climate control, particularly in hot and dry regions. This section aims to summarize the performance metrics for different types of evaporative cooling systems, including direct and indirect systems, as well as hybrid configurations. Performance metrics such as cooling efficiency, energy efficiency, and environmental impact are crucial for assessing the viability of these systems in residential and commercial buildings. Understanding the performance metrics of various ECS technologies is vital for optimizing their application in building design and energy management strategies. Table 3 summarizes the various evaporative cooling systems' performance metrics.

Table 3. Summary of performance metrics for evaporative cooling system.

Cooling System	Cooling Effectiveness (%)	Energy Efficiency (kW/t)	Environmental Impact	Coefficient of Performance (COP)	Design Parameters	Working Principles	References
Direct Evaporative Cooling (DEC)	70–80	0.5–1.0	Minimal; uses water, low emissions	10–20	Requires continuous water supply, high air exchange rate	Air is passed through water-saturated media, lowering air temperature through direct evaporation	[76]

Table 3. Cont.

Cooling System	Cooling Effectiveness (%)	Energy Efficiency (kW/t)	Environmental Impact	Coefficient of Performance (COP)	Design Parameters	Working Principles	References
Indirect Evaporative Cooling (Wet Bulb Temperature)	60–75	0.6–1.2	Low; reduced water use compared to DEC	8–15	Heat exchanger, evaporative cooler, and minimal water usage	Air passes over a heat exchanger cooled by evaporating water; no moisture is added to the supply air	[77]
Indirect Evaporative Cooling (Sub Wet Bulb Temperature)	70–85	0.5–1.0	Low; effective at reducing heat without direct humidity	10–18	High-performance heat exchanger, water-efficient system	Uses sub-wet-bulb temperature to cool air more efficiently than wet-bulb systems without increasing humidity	[78]
Hybrid Evaporative Cooling (Two-Stage IDEC)	75–90	0.5–1.0	Very low; integrates multiple cooling methods	15–25	Combines indirect and direct cooling, dual-stage configuration	First stage: air is pre-cooled indirectly, second stage: air is cooled directly by passing through wet media	[79]
Hybrid Evaporative Cooling (Three-Stage IDEC)	80–90	0.4–0.9	Very low; optimized water use and efficiency	18–30	Involves multiple stages: indirect and direct evaporative cooling	A third stage of indirect cooling enhances performance by cooling air further after the initial two stages	[79]
Hybrid Evaporative Cooling (Multi-Stage IDEC)	85–95	0.3–0.8	Minimal; enhanced performance and reduced emissions	20–35	Advanced multi-stage cooling design with highly efficient heat exchange	Uses multiple indirect and direct cooling stages for maximum cooling with minimum energy consumption	[80]
Evaporative Roof Cooling System	60–75	0.4–0.9	Minimal; reduces roof heat, water-efficient, low emissions	12–25	Requires roof surface for water distribution, ventilation, and drainage	Water is distributed over the roof surface; cooling occurs as water evaporates and reduces roof heat transfer	[81]

9. Discussion

Evaporative cooling systems stand out as promising alternatives to conventional HVAC systems, especially amid the global energy crisis and climate change challenges. As the demand for cooling escalates in response to rising temperatures, conventional air conditioning systems face significant drawbacks, particularly in regions with limited electricity access.

The comparative performance of direct evaporative cooling (DEC) and indirect evaporative cooling (IEC) systems shows that each has advantages and limitations. DEC systems are highly effective in hot, dry climates due to their ability to achieve high cooling efficiency with minimal energy consumption, though they raise indoor humidity levels, which can be problematic in enclosed or humid spaces. IEC systems, which cool air without increasing humidity, offer a more controlled cooling solution suitable for varied climatic conditions but require higher complexity and may benefit from hybridization. Hybrid evaporative cooling systems that combine DEC and IEC methods or incorporate desiccants provide enhanced adaptability across diverse climate zones and reduce the dependence on conventional energy sources.

The research reviewed emphasizes the scalability and adaptability of these systems, especially with recent advancements in hybrid configurations, including solar-assisted systems and multi-stage evaporative cooling. These configurations maximize energy efficiency, reduce operational costs, and expand the feasibility of evaporative cooling for rural and urban infrastructure in regions like Eastern Ethiopia, where water scarcity and low electrification rates pose additional challenges. By recovering water or using nocturnal radiative cooling, these systems could achieve better water management in water-scarce areas.

Additionally, the paper highlights critical gaps in interdisciplinary research on evaporative cooling, especially concerning renewable integration and socio-economic factors. While technical advancements in cooling efficiency are well-documented, there remains limited focus on deploying these systems in underdeveloped regions, taking into account cultural preferences, infrastructural constraints, and economic feasibility. Future research could explore system adaptations for rural contexts, such as using locally available materials, integrating passive cooling methods, or enhancing public awareness of sustainable cooling solutions.

In conclusion, this review affirms the potential of evaporative cooling systems to improve energy sustainability, support thermal comfort, and reduce greenhouse gas emissions in hot and dry regions. However, achieving these benefits on a large scale will require further studies that address the effective integration of renewable resources. The results point to an opportunity for evaporative cooling systems to become a key contributor to sustainable cooling solutions, particularly as energy-efficient, climate-adaptive, and accessible options for regions grappling with both extreme temperatures and limited energy resources.

10. Conclusions

Evaporative cooling systems present a viable and efficient solution for thermal management in buildings, particularly in hot and dry climates. These systems demonstrate significant cooling effectiveness, with hybrid configurations (especially multi-stage systems) achieving rates as high as 95%. Direct and indirect evaporative systems also maintain impressive effectiveness levels between 60% and 85%.

In terms of energy efficiency, evaporative cooling systems consume between 0.3 and 1.2 kW/t, with hybrid and multi-stage systems typically exhibiting the highest efficiency. This low energy consumption, coupled with their reliance on water as a cooling medium, results in minimal environmental impact, making them an eco-friendly alternative to traditional mechanical cooling systems.

The coefficient of performance (COP) for these systems is generally favorable, with hybrid and multi-stage configurations reaching values up to 35, indicating substantial cooling output relative to energy input.

Overall, the performance of evaporative cooling systems is heavily influenced by their design parameters and operating conditions. Advanced designs that incorporate multi-stage cooling and effective water management tend to provide enhanced cooling capacity and energy efficiency. Therefore, evaporative cooling systems are an excellent option for sustainable building practices, contributing significantly to energy savings and reduced environmental impact.

11. Recommendations

This review work investigates that there are few research activities on evaporative cooling systems in eastern Ethiopia and also in Eastern Africa as a whole. Most of these studies have focused on applying evaporative cooling systems for food storage and preservation rather than for building applications.

The feasibility of implementing these systems in both rural and urban areas of Eastern Ethiopia and also Eastern Africa as a whole has not been sufficiently addressed, resulting in a gap in understanding how these technologies can be effectively adopted and scaled. Furthermore, while the existing literature discusses the technical aspects of evaporative cooling, there is a need for more interdisciplinary research that encompasses environmental, economic, and social dimensions.

This gap presents an opportunity for future studies to contribute to a more holistic understanding of how evaporative cooling can mitigate energy challenges and enhance access to cooling solutions in underdeveloped regions like Ethiopia. This initiative could lead to more sustainable and efficient cooling solutions in the area.

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