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# Evaporative Cooling Technologies : From Past to Present

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DOI: <https://doi.org/10.17184/eac.9493>

**Abstract:** Evaporative cooling has served as a crucial method of passive thermal regulation across civilisations for millennia, evolving from rudimentary clay pot techniques to advanced hybrid cooling systems. This study presents a comprehensive historical and technical review of evaporative cooling technologies, highlighting their cultural, architectural, and scientific progression from ancient to contemporary times. Early implementations in Egypt, Mesopotamia, and the Indus Valley illustrate a foundational understanding of thermodynamic principles, using water and airflow to reduce ambient temperatures. The Roman Empire, Persian architecture with windcatchers, and medieval European designs all refined these methods, incorporating indirect and structural adaptations to maximise evaporative effects. During the industrial revolution, evaporative cooling technologies expanded into commercial and industrial applications, with innovations such as water-cooling towers and fan-assisted ventilation systems marking a transition towards mechanised systems. In the 20th and 21st centuries, the development of hybrid systems, solar-powered units, and desiccant-assisted cooling mechanisms has further diversified the scope and efficiency of evaporative cooling. These modern systems address energy efficiency and sustainability concerns, particularly in arid and semi-arid climates, offering cost-effective alternatives to conventional air conditioning. Despite challenges such as diminished performance in humid environments and water consumption, recent advances, including membrane technologies, closed-loop systems, and AI-driven optimisation, continue to enhance the adaptability and performance of evaporative cooling solutions. As global energy demands rise and environmental concerns escalate, evaporative cooling emerges as a sustainable and scalable technology, supporting climate-responsive architecture, agricultural storage, and industrial processes. This article underscores the enduring relevance of evaporative cooling and its potential to shape future thermal management strategies.

**Keywords:** Evaporative cooling; passive cooling; historical technologies; sustainable cooling

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## 1 Introduction

Many past civilisations cleverly employed direct evaporative cooling strategies in their architecture, making use of water storage mechanisms and thoughtfully designed ventilation systems in homes and public buildings. By encouraging evaporation, these techniques effectively lowered indoor temperatures, offering a passive means of climate control [1-2].

This article presents the evolution of evaporative cooling technologies, comparing and contrasting these developments in detail. From ancient practices to modern innovations, the spectrum of evaporative cooling methods will be explored, examining their underlying scientific principles, historical context, and diverse applications. This comprehensive analysis considers not only the advancements in technology but also the cultural and societal influences that have shaped the trajectory of evaporative cooling throughout history.

## 2 Evaporative Cooling

### 2.1 Working Principle of Evaporative Cooling

The process of evaporative cooling functions by bringing air into direct contact with water, promoting the evaporation of the water, as shown in Figure 1 and a consequential decrease in the air temperature [3]. The underlying thermodynamic principle is the absorption of latent heat by the water as it undergoes a phase change, extracting energy from the surrounding air [4-5]. This process is governed by the eq. (1).

$$Q = mL \quad (1)$$

where  $Q$  is the heat absorbed,  $m$  is the mass of the evaporating water, and  $L$  is the latent heat of vaporisation. The efficiency of evaporative cooling depends on factors such as humidity, air circulation, and water availability [6].

Eq. (2) is a key performance metric for evaporative coolers. It indicates how close the outlet air temperature gets to the ideal limit (the wet-bulb temperature).

$$\varepsilon = (T_{dry, in} - T_{dry, out}) / (T_{dry, in} - T_{wet, in}) \quad (2)$$

Where  $\varepsilon$  is effectiveness,  $T_{dry, in}$  is the inlet dry-bulb temperature,  $T_{dry, out}$  is the outlet dry-bulb temperature, and  $T_{wet, in}$  is the inlet wet-bulb temperature.

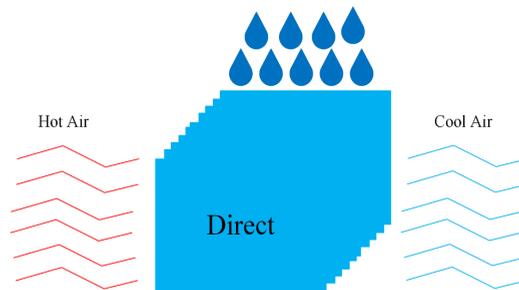


Figure 1: View of evaporative cooling process working principle.

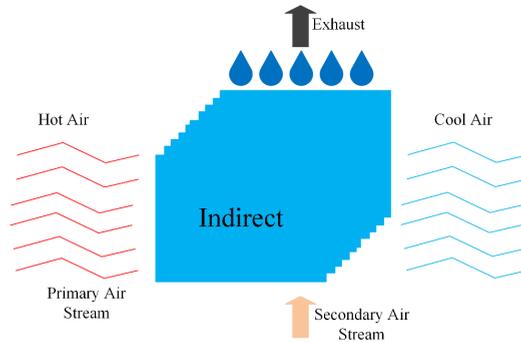
## 2.2 Evaporative Cooling Systems

Currently, evaporative cooling systems are broadly categorised into three main types: direct [7], indirect [8], and hybrid systems [9]. Direct evaporative cooling involves the direct contact of water with the air stream being cooled, increasing the air's humidity as it cools, as shown in Figure 2 a) [10]. Indirect evaporative cooling uses a heat exchanger to cool the air stream without adding moisture, as shown in Figure 2 b) [11]. Finally, hybrid systems combine aspects of both direct and indirect methods to optimise cooling performance, as shown in Figure 2 c) [12-13].

a)



b)



c)

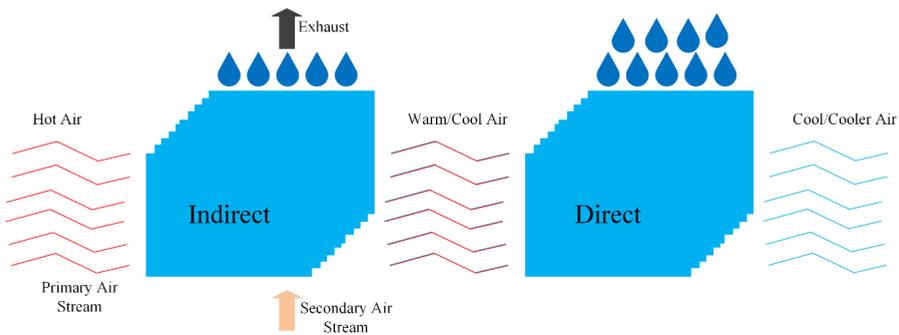


Figure 2: a) Direct, b) indirect, and c) hybrid evaporative cooling methods.

### 3 Historical Development of Evaporative Cooling

The earliest confirmed uses of evaporative cooling appear in ancient Egypt and Mesopotamia [14]. Egyptians hung water-soaked mats and moistened reeds on their walls, utilising prevailing breezes and the evaporative process to cool interior spaces [15-16]. Harking back to antiquity, the resourceful Egyptians pioneered a cooling methodology leveraging porous clay vessels, ingeniously termed the Muscatese Evaporative Cooling System, whereby water permeating through the clay would evaporate, thereby dissipating heat and providing a rudimentary yet effective means of refrigeration as shown in Figure 3. Archaeological evidence suggests that in Mesopotamia, residents employed water channels and surface ventilation techniques to induce evaporative cooling and mitigate indoor temperatures [17]. The Mesopotamians, demonstrating remarkable ingenuity in adapting to their environment, developed various direct evaporative cooling methods to enhance indoor comfort. These included the strategic use of moistened mats, the incorporation of fountains within dwellings, and the implementation of water-based architectural designs, all contributing to a notice-

able reduction in interior temperatures [18]. Although these applied methods are similar to those of ancient Egyptians, they have apparent differences; they represent effective cooling over a wide area. These examples represent early, documented applications of evaporative cooling principles, establishing a historical precedent for later developments in the field. While these methods were less sophisticated than modern technologies, they illustrate an inherent understanding of and reliance on evaporation for cooling purposes. The Indus Valley Civilisation (2600 BCE – 1900 BCE) demonstrated a sophisticated understanding of passive cooling strategies, employing direct evaporative cooling techniques in both domestic and public buildings. These designs often incorporated advanced water storage systems to maintain a consistent water supply, coupled with carefully planned ventilation to maximise the cooling effect within interior spaces [19-20].



Figure 3: Evaporative cooling applied with clay jars in ancient Egypt [21].

Moving into more recent times, advances in evaporative cooling technology have led to a general shift toward more straightforward and more effective methods to implement. This transition marks a significant development, with several societies pioneering this innovative approach and implementing novel techniques to enhance cooling efficiency [22].

During the Roman Empire (200 BCE – 476 CE), significant advancements are made in water-based ventilation and cooling systems [23-24]. Romans ingeniously engineered structures and systems that harnessed the principle of evaporative cooling to lower temperatures, particularly in open-air spaces [25]. While comprehensive documentation of large-scale Roman evaporative cooling projects may be less readily available than for earlier civilisations [26], archaeological evidence reveals innovative approaches to enhancing both air circulation and water evaporation. Roman architects, especially in the design of grand villas and palatial estates, integrated evaporative cooling techniques as shown in Figure 4 [27]. While the precise methods employed might have varied from earlier Egyptian and Mesopotamian practices [26], the fundamental principle of evaporative cooling remained consistent. For instance, Romans likely utilised fountains and pools not only for aesthetic purposes but also to increase ambient humidity [27]. The incorporation of shaded courtyards and the implementation of cross-ventilation strategies maximised air movement and facilitated evaporation, creating more comfortable microclimates [28-29]. In addition, features such as strategically positioned ventilation shafts may have played a crucial role in drawing cooler air into interior spaces [27]. Further investigation into Roman architectural practices and archaeological discoveries could unveil more detailed insights into the specific evaporative cooling systems they employed.

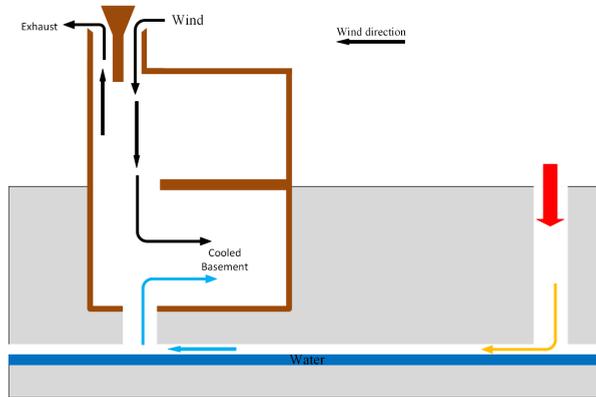


Figure 4: Evaporative cooling application in the Roman Empire [27].

One of the most sophisticated ancient passive cooling strategies is exemplified by the Persian windcatcher (500 BCE – Present) or badgir, an architectural element that served as a natural ventilation and cooling system [30-31]. These structures were designed to direct airflow, often channelling it through subterranean qanats (water channels) or across open water surfaces to facilitate evaporative cooling before introducing the cooled air into buildings, thereby providing a sustainable and energy-efficient method of climate control (indirect evaporative cooling) as shown in Figure 5 [32]. Windcatchers remain a prominent and iconic feature of traditional Iranian and Middle Eastern architecture, demonstrating a deep understanding of sustainable design principles [33-34].

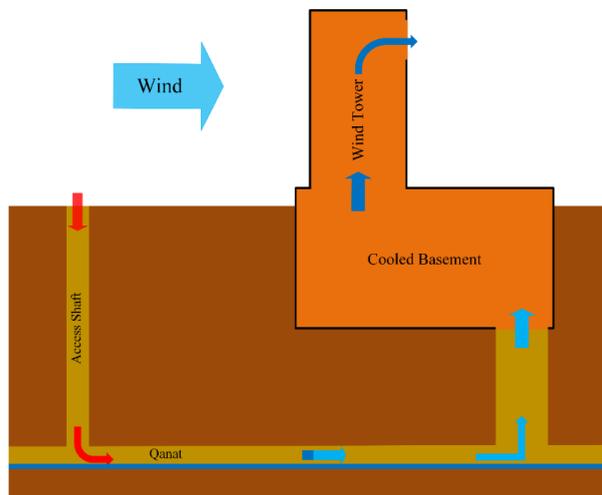


Figure 5: Windcatcher (badgir) [32].

Across regions of China and India (500 BCE – 1500 CE), direct evaporative cooling was facilitated through straightforward yet effective means. Earthenware pots filled with water were commonly placed on rooftops, encouraging evaporation to cool the ambient air. Wealthier families often augmented this process using handheld fans crafted from silk and bamboo, periodically dampened with water, to generate a cooling breeze [35]. These practices demonstrate a greater understanding of evaporative principles for localised climate control with time running [36-37].

Moorish architecture, such as shown in Figure 6, flourishing between 700 CE and 1600 CE, ingeniously integrated water features such as reflecting pools, courtyards, and fountains within homes and public spaces [38]. This design strategy served to enhance indirect evaporative cooling, promoting a comfortable indoor environment through the natural reduction of ambient temperatures. These elements not only provided aesthetic appeal but also played a crucial role in the passive climate control systems of the time (indirect evaporative cooling).



Figure 6: Moorish architecture [38].

During the Medieval period in Europe, passive ventilation strategies and water-based cooling systems were employed in castles and cathedrals [39], aiming to enhance indoor comfort levels through natural means, as shown in Figure 7 [40]. These systems often incorporated the principles of indirect evaporative cooling, leveraging the thermal properties of water and air movement to regulate internal temperatures within these large structures [37 and 41].

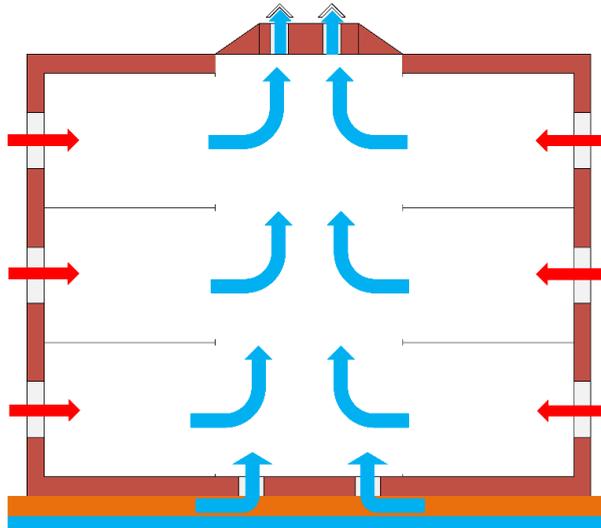


Figure 7: Evaporative cooling and passive cooling strategies of Medieval Europe [39].

In the 5th and 15th centuries, especially during the Umayyad Caliphate of Córdoba in Al-Andalus (modern-day Spain and Portugal), evaporative cooling techniques reached a high level of sophistication. Scholars and engineers devised intricate systems of water channels and open-roof structures to provide cooling in the hot, arid climate [42]. While specific details of these systems can be challenging to ascertain definitively, surviving texts and archaeological evidence point towards innovative designs that maximise airflow and water evaporation for cooling purposes [26]. These advancements represent a significant contribution to the history of evaporative cooling technologies.

During the 19th century, evaporative cooling technologies underwent a significant transformation, paving the way for modern cooling systems [43]. Industrialisation fueled demand for larger-scale cooling solutions, prompting a shift from traditional domestic applications to wider industrial and commercial uses [44]. This period witnessed the integration of evaporative cooling principles into more sophisticated systems, especially within factories and commercial buildings where improved ventilation and temperature control were essential [45]. Innovations such as water-cooling towers, as shown in Figure 8, and powered fans [46] became increasingly prevalent in industrial settings, enabling the effective cooling of larger spaces. These towers facilitate indirect evaporative cooling by dissipating heat from water used in industrial processes, allowing for the recycling of water and improved energy efficiency [47]. These developments marked a departure from smaller, localised cooling methods like evaporative mats and towards more complex, engineered systems designed for industrial applications [48]. Concurrent with the rise of industrial systems, direct evaporative cooling continued to be refined and employed, particularly in drier climates [49]. While mechanical (fan-assisted) refrigeration (hybrid technologies) was emerging during this time [50-51], evaporative cooling remained a practical and cost-effective solution, particularly in regions with limited access to newer technologies or where the climate

favoured its use [52]. These hybrid cooling systems improved upon earlier ventilation methods [39] by actively forcing air movement, contributing to better temperature regulation and indoor comfort [53] in a wider range of settings. By the early 1900s, spurred by growing commercial needs, evaporative cooling began its transition from predominantly residential use to commercial applications in office buildings and other commercial spaces [54]. These combined trends underscore the enduring versatility of evaporative cooling, adapting to meet evolving demands throughout the 19th and early 20th centuries.

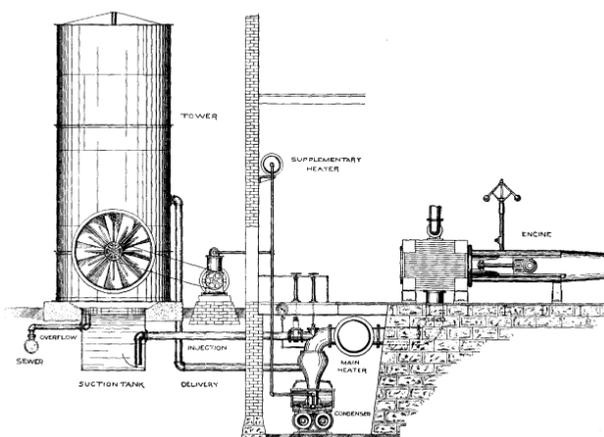


Figure 8: Cooling tower [45].

The 1920-1930s witnessed the rise in popularity of swamp coolers in the United States [27], marking the first widespread commercialisation of this technology. These systems, which often employ a wetted filter pad or similar evaporative medium, effectively lower air temperatures by passing air through a moisture-laden pad, offering a cost-effective alternative to mechanical refrigeration in arid climates (direct evaporative cooling) [55]. This made them a popular alternative to more energy-intensive refrigeration systems, particularly during a period of economic hardship and limited access to electricity in some areas [52].

From the 1950s through the 1980s, evaporative cooling technology saw advancements in efficiency and integration with other systems. Designs improved, leading to better performance and reduced water consumption. This period also witnessed the growing popularity and accessibility of air conditioning technology, which often presented a more comprehensive cooling solution, especially for humid climates [56-60]. As a result, evaporative cooling increasingly became a niche solution, chosen for specific applications or as a supplemental cooling method in certain regions. Despite the rise of air conditioning, evaporative cooling maintained its appeal due to its lower energy consumption and environmentally friendly operation [44], especially in arid and semi-arid climates.

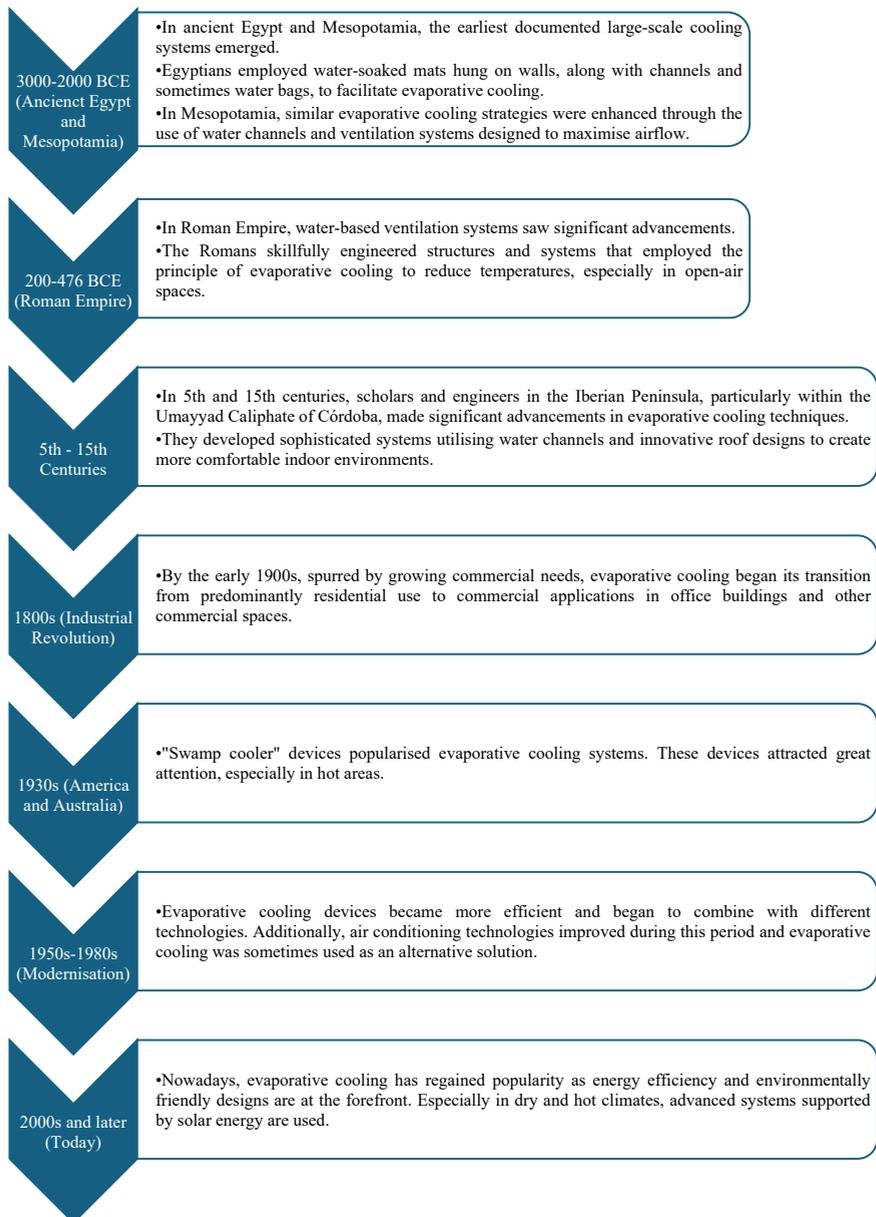


Figure 9: Summary schematic flow chart of the famous historical development of evaporative cooling.

In the 21st century, with the growing emphasis on energy efficiency and environmentally conscious design, evaporative cooling has experienced a resurgence in popularity [61-62]. Modern evaporative coolers, often powered by solar energy [63-64], offer a sustainable cooling solution, especially in arid and semi-arid regions. This renewed interest has also spurred innovation, leading to the development of more efficient and advanced evaporative cooling systems [65]. These factors position evaporative cooling as a relevant and increasingly important technology in the modern era, offering a viable alternative to traditional, energy-intensive cooling methods, particularly in water-stressed regions. Figure 9 schematically illustrates the historical progression of evaporative cooling.

#### 4 Available Applications of Evaporative Cooling Technologies

In this section, the literature is carefully examined, and the evolution of evaporative cooling applications is analysed. The direction, methodology, and key considerations underpinning these developments are carefully highlighted.

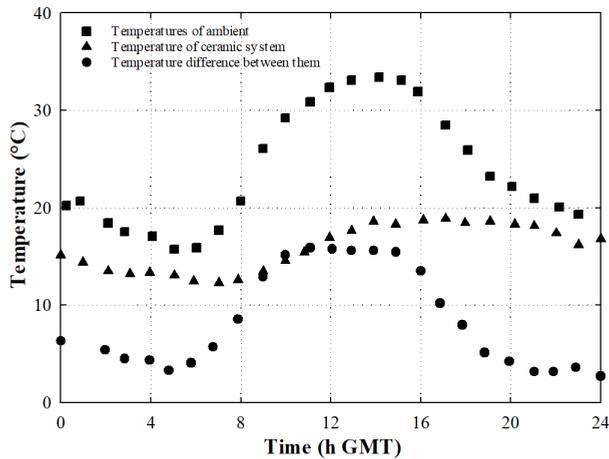


Figure 10: Hourly temperatures of ambient, ceramic system and temperature difference between them [66].

Aimiuwu [66] has explored a ceramic-based storage system that utilises evaporative cooling to maintain a consistently lower temperature than the ambient environment. The study demonstrates that the system, consisting of two nested ceramic chambers, effectively reduced the temperature of the inner chamber through evaporative heat loss. Experimental results show that the inner chamber took approximately 90 minutes to reach equilibrium, cooling at a slower rate than the outer chamber due to the thermal resistance of the ceramic walls. Further observations, as shown in Figure 10, have revealed that the system remained up to 15°C cooler than the ambient temperature during the hottest hours of the day, with a significantly lower daily temperature fluctuation, suggesting greater thermal stability. In addition to its cooling performance, the system's effectiveness in preserving perishable goods has been examined using Indian spinach (*Basella alba*) as a test case. The results have indicated that

the spinach stored within the ceramic chamber remained fresh for 14 days, whereas the control sample, left exposed to ambient conditions, lost 93% of its weight within 12 days due to desiccation. This preservation effect has been attributed to the humid microclimate maintained within the chamber, which reduced moisture loss from the stored vegetables. These findings suggest that evaporative cooling *via* ceramic storage provides a low-cost, energy-efficient alternative for food preservation, particularly in arid and rural regions where refrigeration may not be readily available.

Taha *et al.* [67] have presented the design and experimental evaluation of an evaporative cooler utilising a porous material as shown in Figure 11, specifically charcoal granules, to preserve food by maintaining a significantly lower temperature than the ambient environment. Constructed from galvanised zinc sheets, the cooler features a rectangular enclosure with integrated shelving, a water reservoir, and a controlled wetting system that ensures continuous moisture supply to the charcoal layer, thereby facilitating evaporative cooling. Experimental investigations measured various parameters, including ambient temperature, wet-bulb temperature, internal cooling efficiency, and air circulation effects, demonstrating that the cooler could effectively reduce internal temperatures by 10-13°C below ambient conditions. The findings indicate that larger charcoal granules provided enhanced cooling performance due to improved airflow, while the system maintained sufficiently low temperatures for up to 18 hours even after the cessation of water supply. However, efficiency was observed to decline under conditions such as low air velocity, high wet-bulb temperature, and an unfavourable ratio of enclosure volume to surface area. Although not achieving ideal refrigeration levels, the evaporative cooler offers a promising low-energy solution for extending the freshness of perishable food items in hot climates.

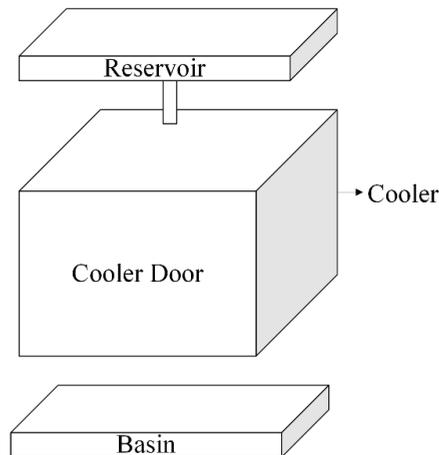


Figure 11: Main components of the evaporative cooler [67].

Anyanwu [68] has presented the design, construction, and experimental evaluation of a porous evaporative cooler, as shown in Figure 12, intended for the short-term preservation of fruits and vegetables. The cooler consists of an inner and outer clay chamber, with the gap between them filled with coconut fibre to enhance water retention, thereby facilitating continuous evaporation and cooling. A water reservoir connected to the system supplies water to maintain the fibre's moisture content, ensuring sustained evaporative cooling. Experimental observations revealed that the cooling chamber consistently maintained temperatures up to 12°C lower than ambient conditions, with the most significant cooling effects observed during the hottest hours of the day, when refrigeration is most required. During trials, fresh produce stored within the cooler exhibited a markedly extended shelf life compared to those exposed to open-air conditions; pumpkins remained fresh for 60 hours, while tomatoes lasted 93 hours, whereas their counterparts deteriorated within 12 to 32 hours in ambient air. The findings suggest that this passive cooling system, constructed using locally available materials, offers a cost-effective and energy-independent alternative for preserving perishable agricultural products in rural settings, where conventional refrigeration facilities may be inaccessible. However, as the performance was found to be highly dependent on environmental factors, its effectiveness may vary across different climatic conditions and seasons.

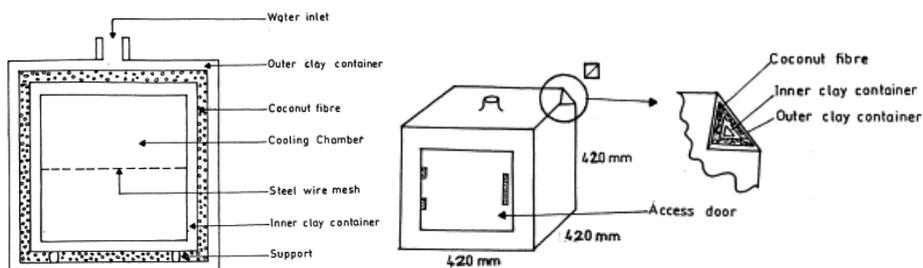


Figure 12: The evaporative cooler [68].

Recent studies have increasingly challenged the long-held assumption that evaporative cooling is neither feasible nor practical for insects, presenting substantial evidence to support the notion that many species are, in fact, capable of employing this mechanism as a means of thermoregulation under extreme environmental conditions. In a comprehensive review of both historical observations and modern experimental findings, Prange [69] systematically have examined the ways in which insects can actively reduce their body temperatures through evaporative water loss, thereby enhancing their ability to survive in hot and arid climates where behavioural thermoregulation alone may not be sufficient. According to the findings outlined in this study, insects have been observed to utilise several distinct pathways for evaporative cooling, including an increase in ventilation within the tracheal system, direct trans cuticular water loss, and the exudation of fluid onto the body surface, all of which contribute to heat dissipation. While certain species are required to rely solely on their internal water reserves to sustain this process, others, such as cicadas, benefit from an abundant external water source in the form of xylem, which enables them to maintain high rates of evaporative cooling without facing immediate risks of desiccation.

One of the most significant factors influencing the effectiveness of this mechanism appears to be body size, with research suggesting that there exists a lower physiological threshold, estimated to be within the range of 100–300 mg, below which evaporative water loss becomes increasingly ineffective due to the rapid depletion of available water and the insect's inability to sustain prolonged exposure to extreme temperatures. Numerous studies have documented cases in which insects, including species such as the migratory locust (*Locusta migratoria*), the grasshopper (*Schistocerca nitens*), and the ground beetle (*Calasoma scrutator*), have successfully maintained their internal body temperatures several degrees below lethal environmental conditions by employing evaporative cooling. Furthermore, experimental data have consistently indicated that as the upper lethal temperature for most insects, typically around 48°C, is approached, rates of evaporative water loss increase significantly, reinforcing the idea that this process plays a critical role in heat regulation. Notably, those species that possess access to an abundant external water source have demonstrated considerably higher rates of evaporative cooling, allowing for more effective and sustained thermoregulation, whereas species that must rely on internal water reserves exhibit more conservative water loss patterns. The findings presented in this review serve to refute previous extrapolations from mammalian models, which had led to the widely accepted belief that insects lacked the physiological capacity for evaporative cooling. Instead, the evidence strongly suggests that this mechanism represents an important evolutionary adaptation that has emerged independently across multiple insect lineages, highlighting the remarkable diversity of thermoregulatory strategies that insects have developed in response to their environmental challenges.

Abdel-wahab [70] have conducted a comprehensive study on the energy and water management of evaporative cooling systems in agricultural structures within the arid climate of Al-Hassa, Saudi Arabia, as shown in Figure 13. In this research, a mathematical model was developed to estimate key parameters, including water evaporation rate, airflow rate, and cooling efficiency, with the aim of optimising these systems for greenhouses and livestock shelters. The study employed a large-scale experimental setup within a multi-span greenhouse (64m × 32m) covered with clear fibreglass and equipped with a fan-and-pad evaporative cooling system. This system operated using fifteen exhaust fans, each powered by a 746 W motor, alongside a centrifugal pump with a 1492 W motor to circulate water. The air temperature, humidity, air velocity, water flow rate, and exhaust air temperature were measured at hourly intervals to validate the proposed model. The findings demonstrated that as ambient temperature increased, the cooling effect followed a linear trend, whereas water evaporation and airflow rates exhibited an exponential increase. For instance, when the ambient temperature rose from 30°C to 46°C, the cooling effect increased by approximately 20%, while water consumption surged by 26 times and the airflow rate by 17 times. Furthermore, the study revealed that increasing the exhaust air temperature from 29°C to 32°C resulted in a mere 0.2% reduction in cooling effect but led to a substantial decrease in water evaporation rate (43%) and airflow rate (42%), indicating that system efficiency could be enhanced by carefully managing exhaust air temperature. Additionally, an increase in evaporative cooling efficiency from 70% to 85% at 44°C was found to reduce water evaporation by 57% and airflow by 64%, highlighting the poten-

tial for significant resource conservation. The study also identified solar radiation as a critical factor influencing cooling load, with an increase from  $800 \text{ W/m}^2$  to  $1000 \text{ W/m}^2$  leading to a 19% rise in water evaporation rate. To address excessive water and energy consumption, Abdel-wahab proposed dynamic regulation of water and airflow rates based on diurnal temperature fluctuations, which was estimated to reduce water consumption by 39% and airflow by 33%. Moreover, covering greenhouse roofs with shading materials or reflective coatings was suggested as an additional strategy to improve cooling efficiency while conserving resources. The study further emphasised the importance of regular maintenance of fans, motors, and pumps, as dust accumulation, misaligned bearings, and inadequate lubrication were identified as significant contributors to unnecessary energy waste. These findings underscore the necessity of optimising evaporative cooling system design and operation, particularly in arid climates, to enhance sustainability and reduce resource consumption.

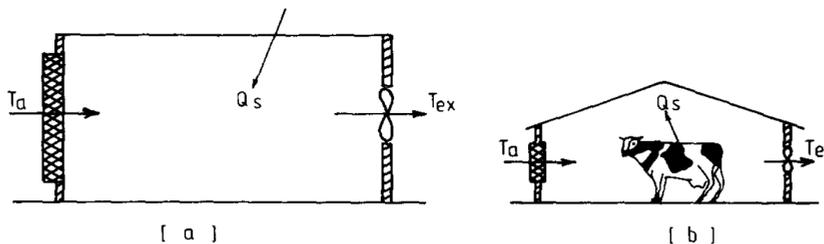


Figure 13: Typical farm structures with evaporative cooling system: a) greenhouse and b) animal shelter [70].

Giabaklou and Ballinger [71] investigated the feasibility and performance of a passive evaporative cooling system that operates through natural ventilation, with the primary objective of providing an energy-efficient, low-cost, and environmentally sustainable cooling solution for buildings in hot and arid climates. The proposed system utilises a vertical cascade of water flowing along guide filaments, maximising the surface area exposure for evaporative cooling. As air naturally passes through this water curtain, it undergoes adiabatic cooling, reducing its dry-bulb temperature while increasing its latent heat content. The study employed numerical simulations to analyse system efficiency, airflow dynamics, and potential indoor temperature reductions under varying climatic conditions. The cooling efficiency was evaluated through saturation efficiency calculations, which demonstrated that the system could achieve significant temperature reductions, particularly in regions with low ambient humidity. A computational model was developed to assess heat and mass transfer coefficients, incorporating Reynolds and Nusselt number correlations to quantify convective heat exchange within the airflow. To validate these findings, the study employed the CHEETAH thermal simulation programme, which modelled the thermal behaviour of a  $10\text{m} \times 10\text{m} \times 2.8\text{m}$  building with continuous window openings and a passive evaporative system integrated into the facade. The simulation results indicated that, under real-world conditions, the evaporative cooling system could reduce peak indoor temperatures by up to  $9.9^\circ\text{C}$ , maintaining an average indoor temperature of  $25.9^\circ\text{C}$  compared to an ambient temperature of  $35.8^\circ\text{C}$ . Furthermore, the system sustained an average relative humidity of 73.2% and an air velocity of  $0.28 \text{ m/s}$ , which were

within the thermal comfort range for occupants. The study also highlighted that adjusting window openings in response to wind speed variations could optimise cooling efficiency, while ceiling fans could be employed to enhance air circulation during periods of low natural ventilation. While financial constraints prevented the construction of a physical prototype, the theoretical analysis strongly supported the feasibility and broad applicability of such a system, particularly for medium-density housing and multi-storey residential buildings. The authors concluded that integrating passive evaporative cooling systems into architectural design could offer a sustainable alternative to energy-intensive mechanical cooling solutions, mitigating peak energy demand pressures in regions with hot climates.

Ibrahim *et al.* [72] have conducted a comprehensive experimental investigation into the performance of porous ceramic evaporators for building cooling applications, as shown in Figure 14. Prototypes with varying degrees of porosity, classified as low, medium, and high, are tested under controlled conditions within an environmental chamber. These evaporators are placed inside a vertically oriented, insulated duct, through which air is passed at a regulated velocity, temperature, and relative humidity. The experimental setup allows for variations in key parameters, including dry bulb temperature (DBT), relative humidity (RH), and supply water pressure, which was set at either 0.4 m or 1.0 m head. Performance data were collected through precise instrumentation, including temperature and humidity sensors, hot-wire anemometers, and barometric pressure measurements. The results indicated that high-porosity ceramic evaporators yielded the most significant cooling effect, with dry bulb temperature reductions of 6–8 K and an associated RH increase of approximately 30%. The most effective configuration involved high-porosity ceramic evaporators arranged in a single-row stack with a high water supply head, achieving a maximum cooling capacity of 224 W/m<sup>2</sup>. Additionally, empirical correlations were derived to quantify the cooling effect as a function of the ambient-to-saturated vapour pressure difference [es–e], providing a predictive framework for the system’s performance. These findings demonstrate the substantial potential of porous ceramic evaporative cooling systems as an energy-efficient solution for passive building cooling applications.



Figure 14: Photo of prototype porous ceramic evaporators [72].

Dai and Sumathy [73] have presented a theoretical and experimental investigation of a crossflow direct evaporative cooler that utilises honeycomb paper as the packing material as shown in Figure 15. The system is designed to function as both a humidifier and an evaporative cooler, particularly suited for arid climates. A comprehensive mathematical model was developed to characterise the coupled heat and mass transfer processes occurring between the falling water film and the airflow. The model incorporates governing equations for both the liquid film and gas phases, as well as interface conditions, enabling the prediction of the interface temperature and the effectiveness of the cooling process. To validate the theoretical framework, an experimental unit was constructed using honeycomb paper with two different wave angles ( $45^\circ$  and  $60^\circ$ ), arranged in alternating layers to enhance mass transfer. The system consists of a water sprinkler, fan-driven airflow, and a water collection basin, where the cooled water is recirculated. Experimental trials were conducted by varying key parameters, including the temperature and humidity of inlet air, air velocity, and feed water temperature. The results demonstrated that the system achieved a temperature reduction of approximately  $9^\circ\text{C}$ , accompanied by a 50% increase in the humidity ratio. Furthermore, the study identified an optimal air channel length of 5–10 cm, which yielded the lowest outlet air temperature. The analysis also revealed that a reduction in honeycomb paper spacing led to a more effective cooling performance due to an increased wetted surface area. The experimental results closely aligned with the theoretical predictions, confirming the validity of the proposed model. These findings highlight the potential of compact, energy-efficient, and environmentally friendly evaporative cooling systems for indoor climate control.

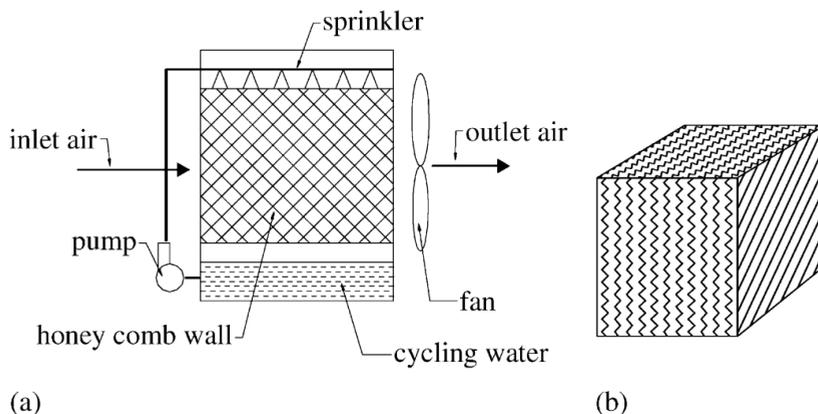


Figure 15: a) The direct evaporative cooler configuration and b) packing material: honeycomb paper [73].

Tang and Etzion [74] have investigated the thermal performance of an improved roof pond cooling system, referred to as a Roof Pond with Gunny Bags (RPWGB) as shown in Figure 16. This system consists of gunny bags floating on a water surface, supported by a grid with polystyrene strips beneath. The main function of the gunny bags is to intercept solar radiation while enhancing evaporative cooling and convective heat dissipation. A detailed simulation model was developed to evaluate

this system's efficiency compared to a conventional roof covered with wetted gunny bags. The model incorporates an empirical correlation for water evaporation rates and considers the heat transfer dynamics of the entire building. The simulations were conducted using climate data from Sede Boqer, Israel, and applied to three building types with varying wall insulation and roof materials. The findings indicate that RPWGB consistently provides superior cooling performance, primarily due to the thermal stratification created within the water pond. This stratification acts as a "thermal diode," limiting heat transfer from the external environment to the deeper water layers while facilitating heat dissipation from the building's interior. The optimal water depth in the pond varies based on the roof type: approximately 20 cm for concrete roofs and around 5 cm for metal-decked roofs. In addition, the study highlights that RPWGB produces a more stable indoor temperature, increases heat flux through the roof, and is less sensitive to variations in the absorptivity of gunny bags compared to traditional wetted gunny bag roofing. Unlike roof ponds with movable insulation, RPWGB is easier to construct and operate while maintaining high cooling efficiency.

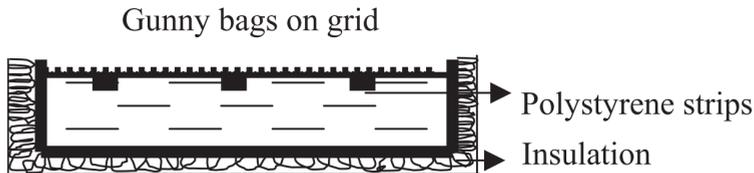


Figure 16: Schematic section of the RPWGB [74].

Zalewski and Gryglaszewski [75] have presented a detailed mathematical model to describe heat and mass transfer processes occurring in evaporative fluid coolers, with a particular focus on systems employing counter current air flow as shown in Figure 17. The proposed model consists of four ordinary differential equations, accompanied by boundary conditions and supplementary algebraic equations, which collectively characterise the heat exchange dynamics between air, water, and the cooled fluid. The methodology introduces a means of adapting the model to the geometric configuration found in bare-tube heat exchangers. To validate the model, a comparative analysis was conducted between the computed results and experimental data derived from an evaporative water cooler test. The findings demonstrated a strong correlation between the theoretical predictions and the observed experimental results. However, a notable enhancement in accuracy was achieved through the introduction of a correction function for the mass transfer coefficient, which refined the agreement between calculated and measured values. The study also provides insights into the interdependence of key parameters governing the heat exchange process, including the influence of water spray density, tube arrangement, and air enthalpy. A computational approach was developed to account for the geometric configuration of the heat exchanger, ensuring that the model remains adaptable to practical applications.

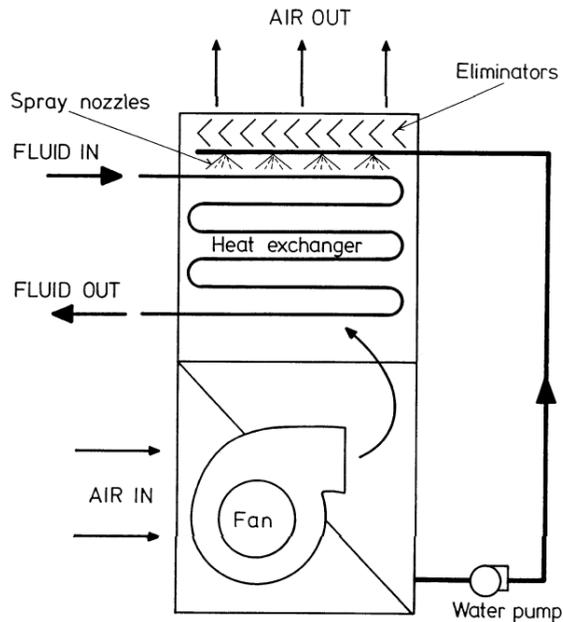


Figure 17: Schematic diagram of evaporative fluid cooler [75].

Armbruster and Mitrovic [76] have presented an experimental investigation into the evaporative cooling of a falling water film on horizontal tubes, arranged in a vertical bundle as shown in Figure 18. The research focuses on the thermal interactions between the falling water and an upward-flowing air stream. The experiments were designed to measure the temperature reduction of water as it falls freely from one tube to the next, thereby assessing the impact of key parameters such as air velocity, humidity, and tube spacing. The results led to the development of an empirical correlation for predicting the evaporative cooling effect. The experimental setup consisted of a closed-loop air flow system where water was uniformly distributed along the top tube and allowed to fall freely onto the tubes below. The water temperatures were recorded at different stages of the process, including just before impact with a tube and after flowing around it. The findings indicated that the majority of the cooling occurred during the free fall of water between tubes rather than during its flow over the tube surface. This cooling was primarily driven by evaporation rather than convective heat transfer. A key observation is that the cooling effect increased with larger tube spacing, higher air velocities, and lower air humidity, while the difference between air and water temperatures had a negligible influence. The study concluded that evaporation at the air-water interface was the dominant cooling mechanism. Based on the experimental results, an empirical equation was formulated to predict the temperature drop of water as a function of flow conditions, air properties, and geometric parameters. This equation provides a valuable tool for the thermal design of evaporative cooling systems.

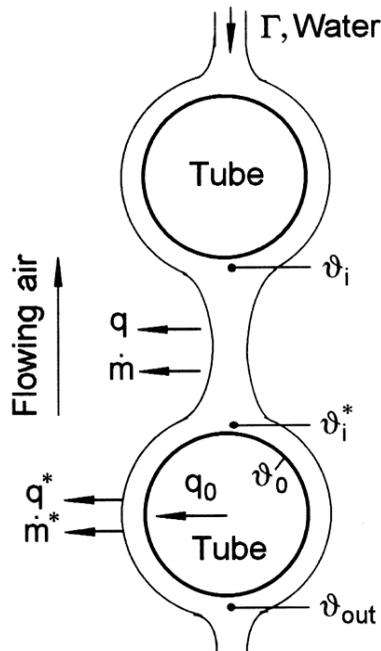


Figure 18: Illustration of heat and mass transfer processes associated with liquid film falling on horizontal tubes [76].

Song *et al.* [77] have investigated the enhancement of cooling performance in an air-cooled finned heat exchanger through the application of thin water film evaporation as shown in Figure 19. A two-dimensional model is developed based on a porous medium approach to analyse heat and mass transfer within a finned channel. The model assumes that the interstitial surface of the heat exchanger is entirely covered by a thin water film, allowing for latent heat transfer through evaporation. The authors derive exact solutions for the temperature and humidity distributions by assuming the Lewis number is unity and the water vapour saturation curve is linear. The results indicate a significant improvement in cooling performance compared to conventional sensible cooling due to the additional thermal conductance introduced by latent heat transfer. However, the study also finds that the effectiveness of evaporative cooling is strongly influenced by fin thickness. If the fin is too thin, the efficiency of heat transfer declines as a result of excessive water evaporation, leading to diminished cooling enhancement. To fully exploit evaporative cooling, the fin thickness must be greater than that used in conventional air-cooled heat exchangers.

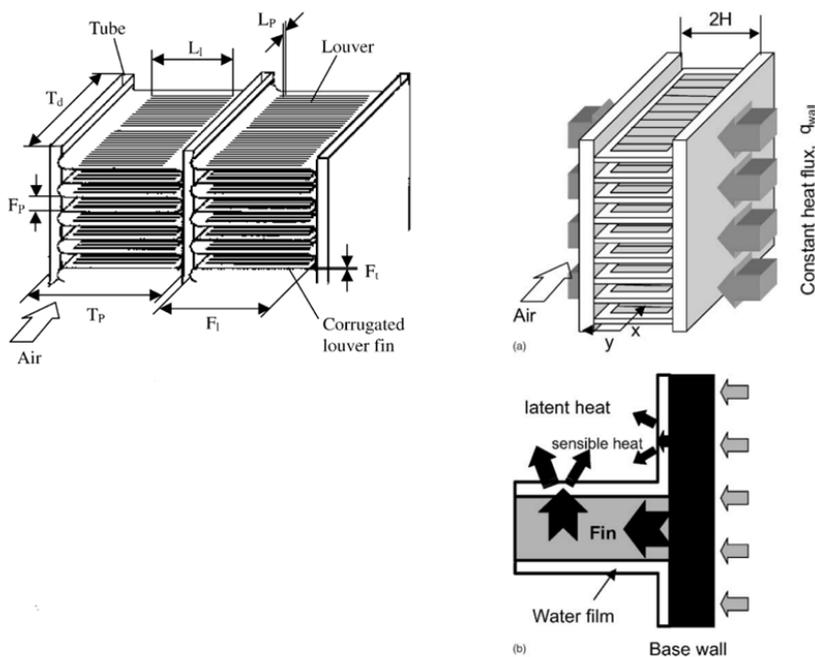


Figure 19: A finned heat exchanger with thin water film on the interstitial surface: a) schematic of the finned channel; b) heat transfer process in the channel covered with thin water film [77].

Qureshi and Zubair [78] have systematically examined the impact of fouling on the thermal performance of evaporative coolers and condensers as shown in Figure 20, recognising fouling as a key factor that leads to the progressive decline in heat transfer efficiency. A comprehensive fouling model is developed based on experimental data from the literature, enabling the prediction of heat transfer deterioration over time. The mathematical model integrates this fouling representation into a broader performance evaluation framework for evaporative coolers and condensers, allowing for a quantitative assessment of thermal degradation under various operating conditions. The results reveal that fouling significantly diminishes the cooling effectiveness of these heat exchangers, with a maximum reduction of approximately 55% for evaporative coolers and 78% for condensers. The study further demonstrates that fouling negatively influences the performance benefits typically associated with lower ambient wet bulb temperatures. As fouling accumulates, the ability of the heat exchanger to exploit these favourable conditions is notably reduced. Additionally, the analysis identifies scale formation, biofouling, and corrosion as primary contributors to performance decline, with calcium carbonate scaling posing a particularly severe threat by drastically reducing thermal efficiency and accelerating equipment degradation. The study employs a numerical approach to validate the fouling model, using data from previous experimental investigations. The mathematical formulation incorporates mass and energy balance equations, convective heat transfer correlations, and empirical relations for scaling effects. By implementing the model in computational

simulations, the study successfully quantifies the deterioration in effectiveness and heat transfer rates under different fouling intensities.

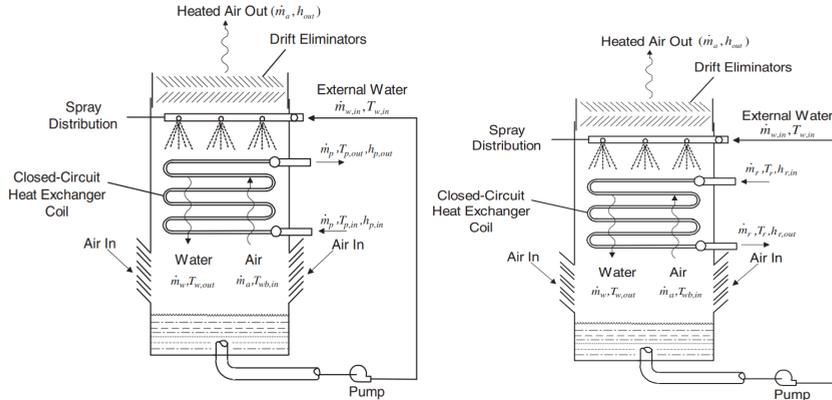


Figure 20: a) Schematic of an evaporative fluid cooler. b) Schematic of an evaporative condenser [77].

Dagtekin *et al.* [79] have investigated the performance characteristics of a pad evaporative cooling system as shown in Figure 21 within a broiler house located in a Mediterranean climate, where summer temperatures frequently exceed  $30^{\circ}\text{C}$ , posing a significant risk of heat stress to poultry. The research aims to evaluate the effectiveness of the cooling system in maintaining a suitable indoor climate for poultry production. The experiment was conducted between 18 July and 3 August 2006 in a commercial broiler house situated near Adana, Turkey. The facility had a capacity of 15,000 hens, and the evaporative cooling system comprised cellulose-based cooling pads (100 mm thick) and six exhaust fans, which facilitated air circulation through the wet pad surfaces. The study employed a systematic approach to measure dry bulb temperature, wet bulb temperature, and relative humidity at both the entry and exit points of the evaporative cooling pads. Temperature and humidity data were collected at different airspeeds using a digital hygrometer-thermometer-anemometer. The cooling efficiency of the system was calculated based on the difference between dry bulb temperatures before and after passing through the pad, as well as the wet bulb temperature of the incoming air. The findings revealed that the average evaporative cooling efficiency varied between 69.2% and 72.0% across the test period. Temperature reductions at the pad exit ranged from  $4.4^{\circ}\text{C}$  to  $7.3^{\circ}\text{C}$ , depending on external weather conditions and airflow rates. The study also observed that higher airflow velocities resulted in improved cooling performance. However, it was noted that the effectiveness of the cooling system decreased as the weight of the poultry increased, leading to higher heat emissions within the broiler house.

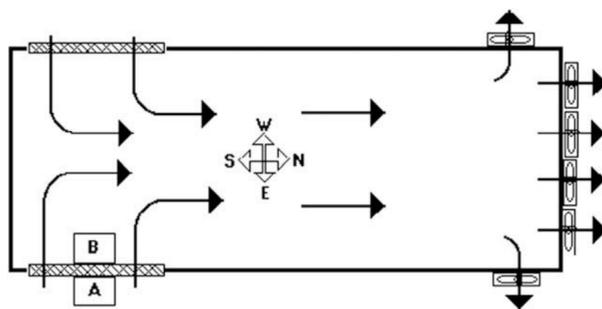


Figure 21: A schematic diagram of the fans, pads and measurement points in the poultry house [79].

Workneh *et al.* [80] have investigated the combined effects of preharvest ComCat® treatment, modified atmosphere packaging (MAP), and forced ventilation evaporative cooling (EC) on the postharvest quality and storability of tomatoes. The research aims to assess the effectiveness of EC in reducing temperature and increasing relative humidity during storage, examine the impact of preharvest ComCat® treatment on physiological and biochemical changes in tomatoes, and explore the synergistic effects of pre-packaging treatments such as chlorine disinfection when integrated with MAP and EC storage. The experimental work is conducted using tomatoes (*Lycopersicon esculentum*, cultivar Malgrove) grown at Haramaya University, Ethiopia. Preharvest ComCat® treatment involved spraying seedlings before transplantation and again at the flowering stage. The tomatoes were manually harvested at the green mature stage and transported in plastic crates to prevent mechanical damage. Postharvest treatments included chlorinated water dipping, MAP using microperforated Xtend® film, and storage in an evaporative cooling chamber. The EC unit maintained an average temperature reduction of 11.5°C and increased relative humidity by 43.9% compared to ambient conditions. The physiological weight loss (PWL) of tomatoes stored in EC was significantly lower than those stored at ambient conditions, with MAP-treated tomatoes exhibiting better retention of moisture and juice content. Preharvest Com-Cat® treatment resulted in lower total soluble solids (TSS), reducing sugars, and total sugars at harvest but contributed to improved postharvest quality by maintaining higher levels of these parameters during storage. Chemical analyses revealed that EC storage delayed ripening and maintained a higher titratable acidity (TTA), while pH increased progressively over time. Microbiological assessments demonstrated that chlorine disinfection effectively reduced aerobic bacteria, moulds, and yeasts during storage. However, the high humidity within the EC unit necessitated proper microbial control strategies. Subjective quality analysis showed that tomatoes stored in EC had a significantly longer marketability period, with MAP-packaged samples maintaining over 70% marketability after 24 days, whereas tomatoes stored at ambient conditions became unmarketable within 12 days.

Tilahun [81] have evaluated the feasibility and economic viability of a low-cost forced ventilation evaporative cooling system for storing fresh fruits and vegetables under the hot and arid climate conditions of Ethiopia. The research aims to investigate the system's ability to reduce storage temperature, increase relative humidity, and ex-

tend the shelf life of perishable produce while remaining economically sustainable for small-scale farmers, retailers, and wholesalers. The experimental evaporative cooler, constructed at Haramaya University as shown in Figure 22, had an internal storage capacity of 0.5 tonnes and was designed with a water circulation system, cooling pads made of charcoal, and a forced air ventilation mechanism. The unit maintained an average temperature reduction from  $36^{\circ}\text{C}$  to  $16.4^{\circ}\text{C}$  and increased relative humidity from 25.4% to 91.1%, which significantly reduced physiological weight loss and preserved the freshness of stored produce. The system operated with a fixed air flow rate of 4.3 kg/s, and the cooling efficiency varied between 55% and 84%, demonstrating its effectiveness in improving storage conditions. The research involved the storage of bananas, papayas, oranges, mandarins, lemons, mangoes, tomatoes, and carrots, assessing their marketability over time. The findings revealed that while fruits and vegetables stored under ambient conditions became unmarketable within 15 days, those kept in the evaporative cooling chamber remained 100% marketable even after two weeks. The study also performed an economic analysis, showing that the evaporative cooling system had a short payback period of less than 1.2 years, making it a cost-effective alternative to mechanical refrigeration for small-scale users.

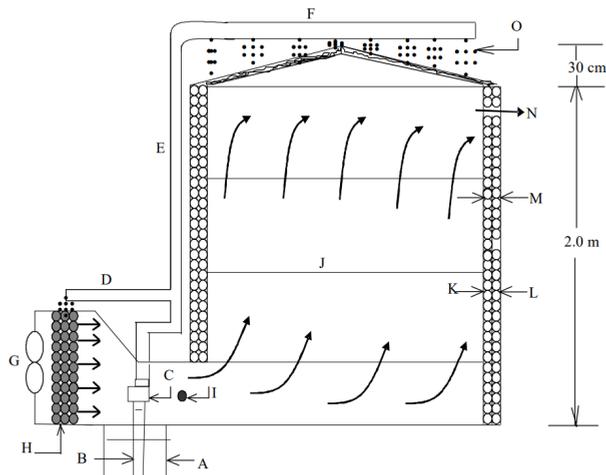


Figure 22: Schematic diagram of an experimental evaporative cooler [81].

Khandelwal [82] has explored the potential for energy savings in a university library building by integrating regenerative evaporative cooling (REC) with an existing water chiller air-conditioning system, as shown in Figure 23. The research employs TRNSYS, a dynamic building simulation software, to analyse the thermal and energy performance of the building under three different air-conditioning scenarios: (i) the existing water chiller system (ii) a simple evaporative cooling system coupled with the water chiller, and (iii) a regenerative evaporative cooling system coupled with the water chiller. The experimental setup models the energy consumption, indoor temperature, relative humidity, and thermal comfort index (PMV) over an entire year. The regenerative evaporative cooling system operates by using a heat exchanger where the process air is pre-cooled before passing through a direct evaporative cooler, reducing

the overall cooling load on the chiller. The study evaluates the feasibility of this approach in terms of energy conservation and thermal comfort. The results indicate that the REC system significantly enhances energy efficiency, achieving a 15.69% reduction in the building's annual energy consumption, compared to a 12.09% reduction when using simple evaporative cooling. Furthermore, the REC system maintains a more stable indoor climate, with reduced temperature and humidity fluctuations, leading to improved thermal comfort. The PMV index, which assesses occupant comfort, remains within the acceptable range (-1 to +1) for most of the year across all three systems, but the REC system provides the most stable comfort conditions.

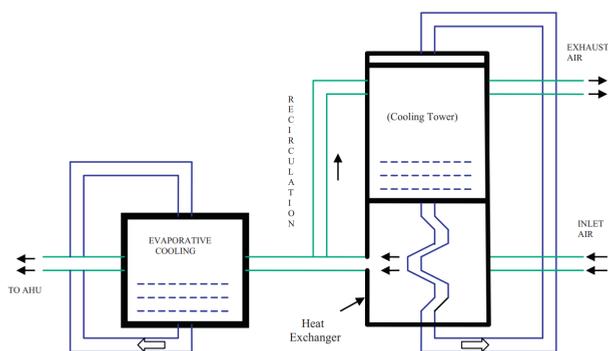


Figure 23: Schematic of regenerative air cooler [82].

El-Awad [83] has examined the feasibility of a solar-assisted winter air-conditioning system that integrates evaporative air coolers (EACs) with a heating process, making them suitable for use in regions with mildly cold but dry winters. The research addresses the limitations of conventional EACs, which are effective in summer but unsuitable for winter conditions due to their cooling effect in already low-humidity environments. To overcome this challenge, the proposed system incorporates a heat exchanger after the evaporative cooling process, where hot water, supplied by a solar water heater, raises the air temperature to maintain comfort. A theoretical model is developed to estimate the system's water and energy consumption, determining the feasibility of using residential-scale solar water heaters for heating the air. The model calculates the necessary hot water flow rate, energy consumption, and operational time based on different heater capacities. It is shown that a 150-LPD (litres per day) solar water heater is sufficient for conditioning a 500-cfm ( $14.4 \text{ m}^3/\text{min}$ ) air flow rate for a minimum of four hours, while larger heater capacities extend the operational time. For instance, a 250-LPD heater supports up to 8 hours of air-conditioning. The results suggest that for sustainable operation, either a larger solar heater or an auxiliary electric heater should be used for extended durations. An economic analysis reveals that the solar-assisted system consumes less energy than a traditional refrigerated air-conditioning system, particularly for air flow rates below 900 cfm. However, due to the high initial cost of solar heaters, a hybrid system combining solar and electric heating is recommended for cost-effectiveness. The study finds that at local energy costs, the optimum operating time for maximum economic savings varies by heater size: 4.03 hours for a 150-LPD heater, 6.71 hours for a 250-

LPD heater, and 8.06 hours for a 300-LPD heater. Over time, energy savings from reduced electricity consumption help recover the additional cost of solar heaters in approximately five years.

Maheshwari *et al.* [84] have investigated the performance of an indirect evaporative cooling system designed to enhance the efficiency of traditional cooling technologies while minimising energy consumption as shown in Figure 24. The research focuses on evaluating the thermodynamic behaviour of the system under various operating conditions, with an emphasis on its cooling effectiveness, energy efficiency, and potential applications in hot and arid climates. A comprehensive experimental setup was developed to assess the thermal performance of the system, which consists of a heat exchanger facilitating indirect evaporative cooling. The system utilises ambient air to cool a secondary air stream *via* water evaporation, ensuring that the cooled air remains unsaturated. Key performance metrics, such as the cooling effectiveness, temperature drop across the exchanger, and energy savings compared to conventional cooling methods, were systematically recorded. The results demonstrate that the indirect evaporative cooling system significantly enhances thermal efficiency, achieving wet-bulb effectiveness values ranging from 70% to 90%, depending on ambient conditions and airflow rates. The system was particularly effective in dry climates, where high evaporation rates facilitated substantial cooling potential. Compared to conventional air-conditioning units, this method offered substantial energy savings while maintaining thermal comfort within acceptable ranges.

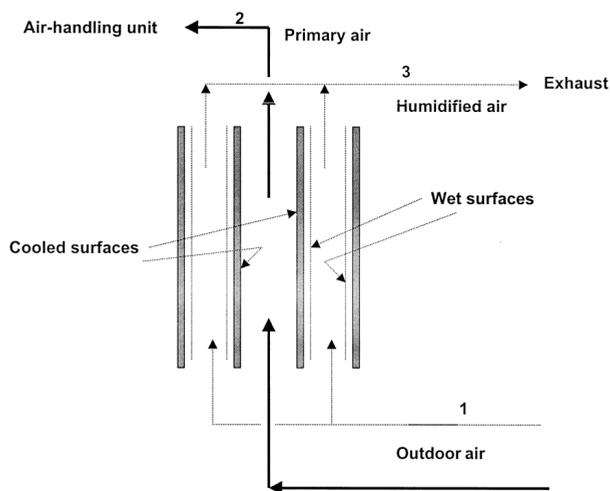


Figure 24: Configuration of indirect evaporative cooler [84].

Cuce [59] have evaluated (the system as shown in Figure 25) the thermal performance of a novel liquid desiccant-based evaporative cooling system (DECS), focusing on its dehumidification efficiency, cooling capacity, and overall energy performance under varying airflow conditions. The system operates in two stages: a dehumidification unit, which reduces moisture using potassium formate solution (74%), and a humidification unit, which cools the air *via* adiabatic saturation. The research was

conducted in a controlled environmental chamber, testing two different inlet air velocities (0.3 m/s and 0.5 m/s) to determine system effectiveness. The results indicate that at 0.3 m/s air velocity, the system successfully lowered relative humidity from 94.7% to 65.5% and reduced air temperature from 38.6°C to 33.3°C, achieving an overall cooling effect of 6.7°C. The dehumidification effectiveness was recorded at 63.7%, while the coefficient of performance (COP) reached 5.5. At a higher airflow velocity of 0.5 m/s, the system lowered relative humidity from 72.5% to 63.6% and reduced air temperature from 38.5°C to 34.2°C, achieving a total cooling effect of 5.8°C. However, the dehumidification effectiveness decreased to 56.1%, and the COP dropped to 4.8, highlighting a trade-off between airflow rate and efficiency. The wet-bulb effectiveness was calculated as 50.0% for 0.3 m/s and 42.4% for 0.5 m/s, demonstrating the system's ability to provide efficient cooling even under humid conditions. Additionally, the humidification effectiveness was 37.3% at 0.3 m/s and 30.2% at 0.5 m/s, further confirming the system's suitability for both hot-arid and humid climates. The findings suggest that lower airflow velocities enhance dehumidification and cooling efficiency, while higher airflow rates improve air circulation but slightly reduce performance. These results confirm that DECS is a cost-effective and energy-efficient alternative to traditional cooling systems, particularly in humid climates where conventional evaporative cooling methods fail. The study recommends further optimisation of desiccant regeneration and system airflow rates to enhance performance and sustainability in real-world applications.

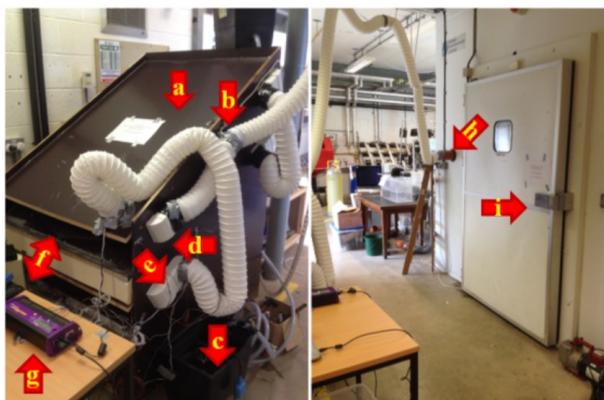


Figure 25: Detailed description of: a) wooden structure of, b) fan for circulating air, c) immersible pump, d) inlet duct to dehumidification, e) outlet duct after humidification, f) collecting ducts for drained water and desiccant, g) data logger, h) inlet fresh air to from conditioned environmental chamber and i) digital and multi-functional environmental chamber [58].

Porumb *et al.* [85] have demonstrated that indirect evaporative cooling (IEC) is a highly effective strategy for reducing energy consumption in fresh air conditioning systems, particularly in office buildings operating in moderate climates such as Cluj-Napoca, Romania. By comparing a conventional cooling system with an IEC-integrated design, the research highlights the significant energy-saving potential of IEC, which reduces peak cooling demand by 41.7% and handles 83.7% of the total cooling load, thereby minimising reliance on chiller-based cooling. As a result, the

annual electricity consumption drops by 80%, from 19,550 kWh to just 3,127 kWh, demonstrating the economic and environmental benefits of IEC adoption. The system effectively operates for 346 hours per year, averaging 69.2 hours per month during the cooling season from May to September, ensuring sustainable and efficient temperature control. The study strongly recommends integrating IEC technology into large office buildings and similar applications to enhance energy efficiency, reduce operational costs, and promote environmental sustainability. Future research should focus on optimising heat exchanger designs, hybrid cooling configurations, and expanding IEC applicability to diverse climatic conditions.

Tominaga *et al.* [86] have employed Computational Fluid Dynamics (CFD) simulations to evaluate the evaporative cooling effects of water bodies in a micro-scale urban environment, focusing on their potential to mitigate urban heat island effects. The research comprises three test cases: a controlled wind tunnel experiment on small-scale water evaporation, a wind tunnel experiment assessing vapour distribution around building arrays, and a field study on a residential neighbourhood with a pond. In the first test case, the CFD model successfully replicates the temperature drop and vapour diffusion above a small water surface, validating its accuracy in predicting evaporative cooling effects. The second test case investigates the complex interaction between wind flow and vapour transport in a built-up urban environment, revealing that CFD can reproduce vapour dispersion patterns around building arrays within a reasonable margin of accuracy. The third test case, conducted in a real urban setting, demonstrates that the presence of a pond reduces air temperature by up to 2°C at pedestrian level, with its cooling influence extending over 100 metres downwind when wind speed reaches 3 m/s at 10 metres height. The findings confirm that evaporative cooling from water surfaces is highly sensitive to wind direction and surrounding urban morphology, making precise CFD modelling essential for urban climate analysis and cooling strategy optimisation. The study concludes that incorporating small water bodies into urban design can significantly enhance thermal comfort, particularly in densely built environments, and recommends further refinements in CFD models to account for heat storage effects and vegetation interactions for more comprehensive urban climate assessments.

Xu *et al.* [87] have experimentally investigated the performance of evaporative cooling pad systems in greenhouses located in humid subtropical climates, focusing on their ability to maintain optimal temperature and humidity levels for plant growth. Conducted in a 2304 m<sup>2</sup> multi-span glass greenhouse in Shanghai, the research evaluates five different working modes: (1) natural ventilation (NV) (2) evaporative cooling alone (EC) (3) evaporative cooling with external shading (EC + ES) (4) evaporative cooling with both external shading and internal thermal screens (EC + ES + IS), and (5) evaporative cooling with circulation fans (EC + ES + CF). The experiments reveal that evaporative cooling alone achieves an efficiency of 75.9%, lowering air temperature from 32.7°C to 28.3°C, but struggles to maintain uniform conditions throughout the greenhouse. The EC + ES mode reduces indoor temperature by 2–3°C compared to ambient conditions, while the EC + ES + IS mode further enhances cooling by an additional 2°C, maintaining indoor air temperatures up to 4°C lower than outside. However, circulation fans do not significantly improve the

horizontal air temperature distribution. The system's energy-saving potential is also analysed, demonstrating that evaporative cooling consumes nine times less electricity than conventional air conditioning. The study concludes that evaporative cooling is a viable solution even in humid climates, particularly when combined with shading methods, and suggests that careful greenhouse sealing, strategic plant placement, and adaptive shading strategies can further optimise cooling performance while maintaining favourable conditions for plant growth.

Miyazaki *et al.* [88] have investigated the cooling performance of a building-integrated evaporative cooling system driven by solar energy, designed to enhance natural ventilation and reduce air-conditioning loads in hot and humid climates. The proposed system integrates a solar chimney with a dew-point evaporative cooler, which is embedded into the ceiling of a building to provide efficient passive cooling. The study employs heat and mass transfer simulations to evaluate the airflow induced by the solar chimney and the cooling effectiveness of the evaporative system under different operating conditions. The results indicate that the system can effectively mitigate internal heat gains in office buildings, achieving a convective cooling load of up to 50 W/m<sup>2</sup>, which corresponds to a 10–50% reduction in peak cooling demand depending on building conditions. The study also identifies the optimal channel width of 25 mm for the evaporative cooling unit, balancing airflow rate and cooling efficiency. The findings confirm that solar chimney-driven evaporative cooling can serve as a viable passive cooling strategy, significantly reducing mechanical ventilation needs and overall energy consumption in commercial buildings. However, further experimental validation is recommended to optimise the system's real-world performance and explore potential hybrid configurations integrating desiccant-based dehumidification for broader applicability in humid climates.

Sultan *et al.* [89] have investigated the feasibility of a solar-chimney assisted evaporative cooling [SCAC (typical SCAC system is shown in Figure 26)] system as a passive air-conditioning solution for agricultural and livestock applications, particularly in arid and semi-arid regions. The system utilises solar energy as the primary driving force during daytime, while an electric fan ensures continuous airflow at night, enabling consistent cooling throughout the day. The research incorporates the Maisotsenko Cycle (M-Cycle), a dew-point evaporative cooling technology that enhances cooling efficiency by lowering air temperature beyond the wet-bulb limit. A thermodynamic analysis is conducted using experimental data from previous M-Cycle studies, and two simplified correlations are developed to predict the system's performance, both of which exhibit strong agreement with experimental results ( $R^2 > 0.95$ ). The findings indicate that the SCAC system effectively reduces air temperature and enhances thermal comfort, making it a viable low-cost alternative to conventional air conditioning in dry and moderate climates. However, its performance is limited in humid regions, where high ambient moisture content restricts evaporative cooling effectiveness. The study concludes that while the SCAC system may not function as a standalone cooling solution, it can significantly reduce air-conditioning loads, lower operational costs, and provide a chilled ceiling effect for agricultural storage and livestock housing. Future research should explore hybrid configurations incorpo-

rating desiccant-based dehumidification to expand the system's applicability to humid environments.

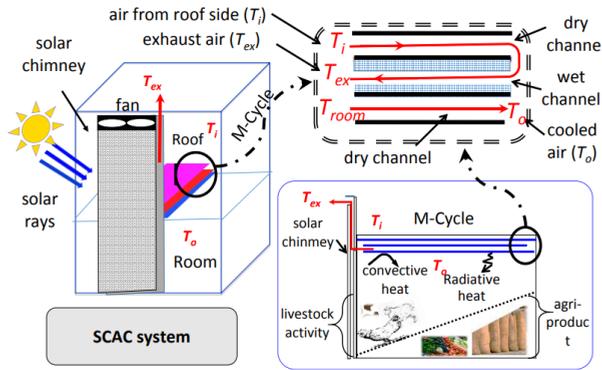


Figure 26: Schematic diagram of SCAC system for agricultural and livestock applications, reproduced from [89].

Yang *et al.* [90] have provided a detailed review of recent advancements in indirect evaporative cooling (IEC) technology, focusing on addressing the inherent limitations of traditional systems, such as temperature constraints and inefficient evaporation. Various material innovations, such as corrugated and porous ceramic wicks, have been introduced to enhance surface wettability and improve the efficiency of water evaporation, significantly boosting the cooling performance. Furthermore, hybrid IEC systems, particularly those combined with heat pumps or mechanical air conditioning devices, are explored for their potential to enhance energy efficiency and reduce consumption, especially in hot-humid climates. Different IEC configurations, including counter-flow, cross-flow, and tubular types, have been optimised for specific environmental conditions, with counter-flow systems excelling in hot, arid areas, and cross-flow systems offering easier installation and lower effectiveness. Additionally, computational models such as computational fluid dynamics (CFD) and regression equations have been developed to optimise system performance based on variables like air velocity, humidity, and channel geometry. The effectiveness of these systems is typically evaluated using key performance indicators such as wet-bulb and dew-point effectiveness, cooling capacity, and coefficient of performance (COP).

Dogramaci and Aydin [91] have presented a comparative experimental investigation of several new organic materials for direct evaporative cooling (EC) applications, specifically in hot-dry climates. The study aims to address the need for locally available, efficient, and environmentally friendly materials that can replace traditional, energy-intensive cooling methods. Five natural materials—eucalyptus fibres (EF), ceramic pipes (CP), yellow stone (YS), dry bulrush basket (DBB), and Cyprus marble (CM)—were tested under controlled conditions to assess their cooling performance in terms of temperature drop ( $\Delta T$ ), relative humidity (RH), cooling capacity, and evaporation rate. The experimental results demonstrated that EF and CP were the most promising materials for EC applications, achieving cooling effectiveness values between 72% and 33% for air velocities ranging from 0.1 to 1.2 m/s, with correspond-

ing cooling capacities of 0.13–0.71 kW for EF and 0.12–0.55 kW for CP. YS also showed competitive results with cooling effectiveness and capacities between 46% and 22%, and 0.08–0.48 kW, respectively. In contrast, DBB and CM exhibited poor performance due to their limited porosity and evaporation capacities, with  $\Delta T$  values below 35% and cooling capacities of less than 0.45 kW. The study found a significant inverse correlation between cooling capacity and effectiveness, highlighting the importance of optimising mass flow rates for improved EC system performance. The optimal operating mass flow rate of 0.063 kg/s was identified, which could be beneficial for optimising the cooling performance of EC systems in future applications. Additionally, the investigation included new performance correlations, such as the relationship between cooling capacity, effectiveness, and mass flow rate, which are crucial for optimising EC systems based on specific environmental conditions. These findings contribute to the development of low-cost, sustainable, and effective cooling technologies using locally sourced materials.

Sun *et al.* [92] have investigated a novel composite fabric that has been developed for passive daytime cooling by combining radiative cooling (PDRC) and evaporative cooling. The fabric consists of a porous polymer coating, P(VdF-HFP), on the upper side, which exhibits high solar reflectivity (90%) and thermal infrared emissivity (83%), essential for effective radiative cooling. The lower side of the fabric is loaded with hygroscopic calcium chloride (CaCl<sub>2</sub>·5H<sub>2</sub>O), which captures water vapour at night and promotes evaporative cooling during the day. This synergistic effect of radiative and evaporative cooling enabled the fabric to achieve a temperature reduction of 10.8 °C under direct sunlight (465 W/m<sup>2</sup>). Key experimental results show that the fabric with the CaCl<sub>2</sub>·5H<sub>2</sub>O loading exhibited excellent cyclic moisture absorption without significant loss in performance, contributing to its sustainability for long-term use. The outdoor test confirmed that the cooling fabric outperformed traditional materials, achieving a superior cooling effect compared to a standard polyester/cotton fabric. The cooling performance was enhanced due to the combined effects of both cooling strategies, with the radiative cooling helping extend the evaporative cooling period. Additionally, the fabric demonstrated impressive antifouling properties, maintaining its cooling performance even after exposure to contaminants, owing to the hydrophobic nature of the polymer coating. The fabric's self-cleaning ability further enhances its practicality for outdoor applications. These findings highlight the potential of this composite fabric in reducing energy consumption and greenhouse gas emissions by providing an affordable, effective passive cooling solution for various applications.

Li *et al.* [93] have presented a novel tandem radiative/evaporative (TRE) cooler system, which efficiently combines the benefits of both radiative and evaporative cooling. This dual-functional passive cooling system addresses the inherent limitations of traditional cooling methods. Specifically, while evaporative cooling typically requires a continuous water supply, and radiative cooling depends heavily on favourable weather conditions, the proposed system overcomes both challenges. The innovative design uses a bilayer polymer structure: a cellulose acetate (CA) fibrous network that reflects sunlight for radiative cooling, combined with a poly (vinyl alcohol) (PVA)-CaCl hydrogel underlayer that passively harvests water from the atmosphere at night for evaporative cooling during the day. This ensures continuous cooling regardless of

external weather conditions, a significant advantage over traditional methods. The cooling power of this tandem system is noteworthy. Under standard conditions with an ambient temperature of 30°C, it achieves a cooling power density of approximately 470 W/m<sup>2</sup>, surpassing both radiative cooling (150 W/m<sup>2</sup>) and pure evaporative cooling (320 W/m<sup>2</sup>). This performance is validated through various experimental setups, demonstrating the system's robustness and high cooling potential. The TRE cooler operates efficiently even in suboptimal weather conditions, such as cloudy or rainy days, maintaining sub-ambient cooling temperatures. Furthermore, the system has been tested in diverse climatic zones, including arid, subhumid, and humid climates, where it consistently outperforms conventional systems, offering more than a 7°C reduction in temperature compared to radiative coolers alone. The study also highlights the design's scalability and cost-efficiency, with a focus on simple material processing methods, such as electrospinning for the CA fibrous network and freeze-drying for the PVA-CaCl hydrogel. Additionally, the system's high reflectivity (0.93) and strong mid-infrared emissivity (0.94) ensure that it maintains optimal performance throughout the day, even when moisture is absorbed for evaporative cooling. In comparison to traditional evaporative cooling technologies, which often require complex systems and high initial costs, the TRE cooler offers a more practical, environmentally friendly alternative. In conclusion, the tandem radiative/evaporative cooler is a significant advancement in passive cooling technology, demonstrating excellent performance across various environmental conditions, making it a promising solution for large-scale applications in buildings, vehicles, and electronics.

Cuce *et al.* [60] have presented a comprehensive theoretical analysis of an innovative indirect-contact evaporative cooling system (ICES) aimed at enhancing energy efficiency in residential buildings. Given that heating, ventilation, and air conditioning (HVAC) systems account for 40% of energy consumption in the construction sector, this research sought to optimise the performance of ICESs through mathematical modelling. The investigation specifically assessed the effects of key operational parameters, including the size of the water-spraying unit (WSU), the velocity of the working air (WA), and the hydraulic diameter (Dh) on the evaporated water vapour (EWW) rate. Findings indicated that increasing the Dh and WSU size led to a greater amount of EWW, whereas higher WA velocity diminished evaporation. Furthermore, to achieve adiabatic saturation, the WSU needed to be at least 8 metres in length. A test residence was constructed in the southeastern UK to validate the theoretical findings, featuring a polycarbonate heat exchanger (PHE) integrated beneath the roof. Additional results demonstrated that lower WA velocities resulted in a reduced outlet air temperature, which is critical for optimising cooling performance. The study also highlighted the influence of external air temperature and humidity on the efficiency of the system, showing that an inlet air humidity below 50% was optimal. Moreover, if the fresh air outlet temperature exceeded 35°C while relative humidity surpassed 40%, indoor thermal comfort could not be maintained. These insights contribute to the development of low-carbon residential buildings by providing a robust optimisation framework for ICESs.

Wu *et al.* [94] have introduced an innovative solar-driven co-generation system named AC-CTEM, which integrates thermoelectric power generation and evaporative cool-

ing to enhance the simultaneous production of electricity and purified water. The system employs a photothermal layer composed of multi-walled carbon nanotubes (MWCNTs) and polydimethylsiloxane (PDMS) to maximise solar absorption, while an aerogel evaporator, cross-linked with chitosan and polyurethane, facilitates efficient evaporation by reducing the enthalpy of water vaporisation. The experimental findings reveal that under a solar irradiance of  $1 \text{ kW/m}^2$ , the system achieves a water evaporation rate of  $1.465 \text{ kg/m}^2 \cdot \text{h}$  and a maximum power output density of  $0.29 \text{ W/m}^2$ . Further enhancement through Fresnel lenses and wind-assisted cooling resulted in a significantly higher evaporation rate of  $3.445 \text{ kg/m}^2 \cdot \text{h}$  and an open-circuit voltage of  $201.12 \text{ mV}$ . Notably, the study also demonstrated the system's effectiveness in desalinating high-salinity water (20 wt%) and purifying various wastewater types, including heavy metal-contaminated and dye-laden effluents. Long-term operational stability was confirmed through 10-hour continuous desalination experiments, with no observable salt crystallisation on the aerogel surface, ensuring sustained performance. The AC-CTEM system's practical application was validated by successfully cultivating grass seeds using desalinated water and powering electronic devices *via* stored thermoelectric energy. These results highlight the system's potential as a sustainable solution for addressing global water scarcity and energy challenges, particularly in remote and resource-limited environments.

Zhang *et al.* [95] have presented an experimental evaluation of a novel hybrid air-conditioning system that integrates air cooling and evaporative cooling (ACEC-AC) to enhance data center cooling efficiency. The research addresses critical challenges in conventional air conditioning for data centers, such as high-temperature shutdowns, excessive energy consumption, and the underutilisation of natural cooling resources. The system is particularly designed for regions with high outdoor temperatures and significant dry-bulb to wet-bulb temperature differences. Experiments conducted in an enthalpy difference laboratory demonstrated that the system, when operating in wet mode (combining air and evaporative cooling), significantly outperforms traditional air-cooled systems. At an outdoor temperature of  $35.60^\circ\text{C}$  (dry-bulb) and  $29.95^\circ\text{C}$  (wet-bulb), the system achieved a coefficient of performance (COP) of 3.85, marking a 21.45% improvement over dry mode and a 16.16% enhancement compared to conventional Packaged Computer Room Air Conditioning (CRAC) units. Additionally, the study found that in cities like Guangzhou, where the temperature difference between dry and wet bulbs is considerable, the ACEC-AC system results in an annual operational cost reduction of over 34.16%. The study also evaluates various operational modes, including dry mode for emergency scenarios (such as water shortages) and liquid pump mode for efficiently utilising outdoor cold sources at low temperatures. Performance analysis reveals that in liquid pump mode at  $5^\circ\text{C}$  (dry-bulb), the system achieves a COP of 15.89, a 30.33% improvement over traditional CRAC units. The study concludes that the ACEC-AC system is a highly effective energy-saving solution that enhances cooling efficiency, optimises heat exchange, and significantly reduces energy costs, making it a promising innovation for the future of data center cooling.

Zhang *et al.* [96] have presented an experimental investigation into a desiccant-assisted two-stage evaporative cooling system (DETEC) designed to enhance air con-

ditioning performance in hot and humid environments. The motivation behind this research stems from the need for more energy-efficient and eco-friendly cooling solutions, as conventional vapour compression refrigeration (MVCR) systems exhibit high energy consumption and rely on refrigerants with a high global warming potential. A key issue addressed by the DETEC system is the effective management of both heat and moisture loads, which conventional evaporative cooling methods struggle to decouple efficiently. The experimental setup incorporates a two-stage heat exchanger to separate heat and moisture processing, allowing for improved cooling efficiency and moisture removal. The system was tested under three different climatic conditions, revealing that it could achieve a coefficient of performance (COP) ranging from 11.3 to 18.4 while maintaining compactness and operational simplicity. Under optimised conditions, with a low wind speed (1.0 m/s), high desiccant concentration (35%), and substantial desiccant flow (0.09 kg/s), the system was able to provide a minimum supply air temperature of 18.44°C. In high heat and humidity conditions, the DETEC system effectively extracted 20% of the product air for secondary cooling while maintaining an effective COP of 3.63. The study further demonstrated that by optimising operational parameters such as desiccant concentration and airflow rate, the system could balance cooling performance with energy efficiency. Compared to conventional systems, the DETEC system exhibited significant advantages in reducing energy consumption while providing independent temperature and humidity control.

Modern applications extend far beyond industrial settings. Evaporative cooling is now integrated into HVAC systems, offering an energy-efficient and environmentally conscious alternative to traditional air conditioning, especially in regions with dry climates. Enhanced evaporative cooling technologies incorporate desiccants and membranes to boost performance, while hybrid systems combine evaporative methods with conventional air conditioning for optimal energy consumption. These advancements reflect a commitment to sustainable climate control and a growing awareness of the environmental impact of cooling technologies.

Evaporative cooling technologies have undergone significant advancements, evolving from rudimentary clay pot cooling systems to highly sophisticated hybrid and indirect evaporative cooling mechanisms. While historically confined to passive applications in traditional architecture and small-scale agricultural storage, contemporary implementations have expanded into large-scale industrial cooling, sustainable urban planning, and precision-controlled agricultural environments.

As global concerns surrounding energy consumption, water scarcity, and climate change intensify, the future of evaporative cooling appears increasingly promising. Recent developments in solar-assisted evaporative cooling, desiccant-enhanced hybrid systems, and AI-integrated adaptive cooling solutions indicate a paradigm shift towards optimising efficiency while minimising environmental impact [97]. Furthermore, interdisciplinary research integrating nanomaterials, phase-change materials, and computational fluid dynamics simulations is expected to yield more resilient and adaptable cooling technologies.

Despite these advancements, challenges remain—particularly in humid climates where direct evaporative cooling loses efficiency due to high ambient moisture levels. In

response, researchers are actively exploring hybrid solutions that leverage indirect cooling methods alongside sorption-based dehumidification and membrane-assisted cooling systems, ensuring enhanced performance in diverse climatic conditions.

In conclusion, evaporative cooling continues to serve as a cornerstone of sustainable thermal management, offering a viable alternative to energy-intensive refrigeration technologies. By fostering continued innovation and refining system efficiencies, the integration of smart evaporative cooling networks into future climate-responsive designs holds the potential to revolutionise both residential and commercial cooling sectors, paving the way for a more sustainable and energy-efficient built environment.

## 5 Conclusions

Evaporative cooling technologies have undergone a remarkable transformation from their earliest implementations in ancient civilisations to the highly sophisticated and energy-efficient systems seen today. Historically, passive evaporative cooling methods were widely adopted across diverse climatic regions, leveraging simple yet effective principles to provide thermal comfort. Over time, advances in engineering, material science, and system integration have led to the development of more efficient cooling technologies, including direct, indirect, and hybrid evaporative cooling approaches. These developments have significantly enhanced the applicability of evaporative cooling in modern industrial, commercial, and residential settings, particularly in regions characterised by hot and arid climates.

The research presented in this study has provided a comprehensive review of evaporative cooling technologies, outlining their historical progression, working principles, and technological advancements. A critical evaluation of these systems demonstrates that while direct evaporative cooling remains the most straightforward and cost-effective approach, indirect and hybrid cooling solutions have gained prominence due to their ability to provide efficient cooling without excessive humidity buildup. The integration of desiccant-assisted cooling, regenerative evaporative systems, and hybrid configurations with mechanical refrigeration has further expanded the potential applications of evaporative cooling, enabling its implementation in more diverse climatic conditions, including humid environments where conventional evaporative methods have traditionally been less effective.

The study has also highlighted key performance metrics for evaporative cooling systems, including cooling effectiveness, energy efficiency, and water consumption. The findings indicate that modern evaporative cooling technologies offer substantial energy savings compared to traditional air conditioning systems, with reductions in power consumption ranging from 30% to 80% depending on system design and environmental conditions. Furthermore, the introduction of advanced materials, such as porous ceramics, polymer membranes, and nanostructured coatings, has led to significant improvements in heat and mass transfer efficiency, thereby enhancing overall cooling performance.

One of the critical challenges associated with evaporative cooling remains its dependence on water availability, particularly in regions where water scarcity is a growing

concern. However, recent innovations in closed-loop and water-recycling evaporative systems, as well as solar-powered desiccant cooling technologies, offer promising solutions to mitigate this limitation. Moreover, the potential for integrating evaporative cooling with renewable energy sources, such as photovoltaic solar panels and geothermal heat exchange systems, further underscores the sustainability of these technologies in addressing global climate control challenges.

The review has also underscored the increasing role of evaporative cooling in sustainable building design, with applications extending beyond conventional air conditioning to include passive cooling strategies in architecture, urban planning, and agricultural storage. The deployment of evaporative cooling in greenhouses, data centres, and industrial processes demonstrates its versatility and adaptability across various sectors. Additionally, computational fluid dynamics (CFD) modelling and artificial intelligence (AI)-based control strategies have been identified as emerging trends in the optimisation of evaporative cooling performance, enabling real-time adjustments to operating conditions and further enhancing system efficiency.

As global energy demands continue to rise and the environmental impact of traditional cooling methods becomes more pronounced, evaporative cooling represents a viable and sustainable alternative. Future research should focus on further improving the efficiency of hybrid evaporative cooling systems, developing more resilient and water-efficient cooling media, and exploring novel integration strategies with renewable energy sources. Additionally, the long-term viability of evaporative cooling in the face of climate change necessitates further investigations into adaptive system designs capable of operating efficiently under varying atmospheric conditions.

In conclusion, evaporative cooling technologies have evolved into a critical component of modern energy-efficient cooling solutions. Through continued research and technological advancements, these systems have the potential to play a pivotal role in reducing global energy consumption, minimising carbon emissions, and providing sustainable climate control solutions for future generations. The integration of innovative materials, renewable energy, and intelligent control systems will further enhance the performance and applicability of evaporative cooling, solidifying

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