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**Research Article**

# Nature-Inspired Design Solutions for Passive Cooling Systems

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**Abstract**

The increasing demand for energy-intensive cooling systems highlights the urgent need for sustainable alternatives in architectural design. This research investigates a nature-inspired passive cooling strategy, drawing from the thermoregulatory mechanisms of a camel's nasal cavity. The study explores how biological principles of heat and moisture exchange can be translated into architectural applications to mitigate indoor heat loads. A biomimetic prototype was developed using coconut coir as the evaporative medium within a wind catcher system. Coconut coir was selected for its porous texture and moisture retention capacity, enabling effective evaporative cooling. Thermodynamic analysis and performance testing were conducted under hot and arid climatic conditions of Kalburgi, India. Results demonstrate a cooling capacity ranging from 54.9 to 73.8 kJ/h, with leaving air temperatures between 33.7 °C and 34.4 °C under varying air velocities. While higher airflow increased overall cooling capacity, it slightly reduced saturation efficiency, indicating a trade-off between efficiency and load capacity. The findings confirm the feasibility of employing coconut coir as a sustainable and locally available cooling medium. This study underscores the potential of biomimicry to reduce reliance on conventional air conditioning, offering cost-effective, eco-friendly solutions for hot and dry climates.

**Keywords:** Biomimicry, Passive Cooling, Camel Nasal Cavity, Coconut Coir, Sustainable Architecture, Evaporative Cooling

## 1. Introduction

The pressing global challenges of climate change and dwindling resources necessitate innovative approaches to sustainable architecture, particularly in mitigating the energy demands associated with cooling (Hays et al., 2024). This paper explores nature-inspired design solutions as a paradigm for developing passive cooling systems, drawing lessons from biological adaptations that efficiently manage thermal regulation in diverse environments (Hays et al., 2024). This approach, often termed biomimicry, seeks to emulate the forms, processes, and systems found in nature to address human design challenges, offering inherently sustainable and energy-efficient solutions for built environments (Bouabdallah et al., 2016). This growing discipline leverages the wisdom of natural selection, which has optimized organisms over millennia to thrive within their environmental constraints, to develop architectural innovations that minimize thermal loads and enhance occupant comfort (Bijari et al., 2025). This paper delves into various biomimetic strategies, examining how principles such as thermoregulation in animals can be translated into effective passive cooling mechanisms for buildings (Yuan et al., 2017). This includes an analysis of how strategies such as adaptive building envelopes, optimized ventilation pathways, and evaporative cooling techniques, directly inspired by natural phenomena, can significantly reduce reliance on conventional energy-intensive cooling systems (Siripurapu et al., 2023). This interdisciplinary approach merges principles from biology, engineering, and architecture to create resilient and environmentally conscious structures (Bankar & Jogdand, 2020).

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Therefore, this research endeavors to elucidate the functional mechanisms of a camel's nasal cavity, with the objective of developing a building prototype that emulates this process. The selection of appropriate materials capable of fulfilling the desired function is paramount; in this study, coconut coir was chosen for its capacity to retain moisture, thereby facilitating the intended evaporative cooling effect. Subsequently, the efficacy of this process within a building context is validated through computational analysis and prototype testing. This investigation underscores the potential of biomimicry to address the urban heat island effect and reduce building energy consumption, particularly in hot and humid climates (Araque et al., 2021) (Sheikh & Asghar, 2019).

## 2. Literature Review

Biomimicry as a solution has garnered significant attention for its potential to provide sustainable and energy-efficient solutions in the built environment, particularly in the realm of passive cooling (Lotfabadi et al., 2016). This interdisciplinary approach, rooted in observing and emulating nature's time-tested designs, offers novel pathways to mitigate the escalating energy demands of conventional air conditioning systems (Solano et al., 2023). Natural systems, honed by evolutionary pressures, provide a rich repository of strategies for thermal management, inspiring adaptive architectural forms and skins that respond dynamically to environmental conditions (Showkatbakhsh & Kaviani, 2020). This paradigm shift integrates principles such as biomaterial applications, responsive building envelopes, and adaptive ventilation strategies to enhance thermal comfort while minimizing environmental impact (Araque et al., 2021) (Ba et al., 2025). Biomimetics, which integrates biological and engineering principles to foster sustainable development, offers a framework for solving complex problems through nature-inspired innovations (Araque et al., 2021).

Thermoregulation is the biological process of maintaining an organism's internal temperature within a consistent range, balancing heat gain and loss despite external environmental variations.(Abdullah et al., 2018) Organisms require specific temperature ranges for optimal physiological functioning, which has driven the evolution of numerous adaptations and behavioral strategies for effective thermal management(Carroll et al., 2021).

Diverse species utilize various mechanisms for evaporative cooling, including sweating, panting, and gular fluttering(Abram et al., 2016; McKinley et al., 2017; Peeks & Badarnah, 2021; Samara, 2019). Evaporation occurs when air moves across a moist surface, facilitating the transfer of heat away from that surface. While sweating is a common cooling mechanism in mammals such as humans, camels, horses, and some kangaroos, birds, which lack sweat glands, employ gular fluttering. This process involves the rapid vibration of the floor of the mouth with the mouth open, thereby regulating their body temperature.(McKinley et al., 2017) This rapid movement increases airflow over moist membranes in the mouth and throat, enhancing evaporative heat loss (Siripurapu et al., 2023). Similarly, the design of building skins can draw inspiration from the intricate structures and functionalities of natural organisms, thereby optimizing energy performance and reducing overall consumption (Nagy & Osama, 2016).

Camels possess a distinctive nasal cavity adaptation that enables their survival in extreme desert environments. This adaptation facilitates evaporative cooling, thereby cooling the inhaled atmospheric air prior to its entry into the body. The camel's nasal structure is characterized by a coiled surface, referred to as the nasal turbinate, which is enveloped by a highly vascularized, moist mucous membrane.(Mohammed et al., 2025) This lining pre-cools the inhaled desert air as it traverses the turbinate surface. With an approximate surface area of 1000 $cm^2$, the turbinate is sufficiently extensive to initiate evaporative cooling during airflow. Camels maintain an internal body temperature typically between 37-38°C, and inhaled air must attain this range before entering their lungs.(Hoter et al., 2019) The nasal turbinate plays a critical role in regulating the temperature of respiratory air. As the camel inhales, air flows over the turbinate surface, inducing the evaporation of mucus. This process cools the turbinate surface and saturates the air with moisture. Convection subsequently transfers heat, warming the inhaled air to the body's temperature as it progresses toward the lungs. Conversely, during exhalation, the warm, humid air encounters the cooler turbinate surface, resulting in further cooling and the condensation of water vapor. In response to the elevated external temperatures characteristic of deserts, camels augment blood flow from the brain to the nasal turbinate, thereby enhancing these cooling mechanisms.(Hoter et al., 2019)

## 3. Methodology

The research methodology is segmented into distinct phases, commencing with theoretical exploration, progressing to experimental development, and culminating in performance evaluation and analysis. This approach integrates biomimicry, prototype construction, thermodynamic calculations, and analytical assessment to ascertain the viability of a camel-inspired cooling system. The methodology is detailed as follows.

### 3.1 Literature Review

The initial phase involves a comprehensive review of existing literature pertaining to the anatomical structure and functional mechanisms of the camel's nasal cavity, recognized for its distinctive thermoregulatory capabilities. The camel's proficiency in water conservation while concurrently cooling inhaled air serves as the biological precedent for this research. Through this review, the physiological principles governing heat exchange and moisture retention are identified and subsequently translated into applicable engineering concepts. This stage is crucial for establishing the theoretical framework upon which the biomimetic prototype will be developed.

### 3.2 Prototype Development

Subsequent to the literature review, a prototype cooling unit is conceptualized and constructed to emulate the thermal regulation processes observed in the camel's nasal cavity. A prototype model was constructed to empirically validate the operational principles of the described cooling process. The room model utilized a two-way wind catcher with the following specifications: a floor area of 12m² (3m x 4m). The wind catcher itself measured 1m x 1.5m and extended 1.8m above the roof, with a total length of 3m.

Coconut coir is utilized as the medium for air passage within the wind catcher. Its porous, fibrous texture facilitates moisture retention, enabling the evaporative cooling of air as it permeates the coir and absorbs water vapor before entering the interior space. Initial designs, where the entire wind catcher opening was covered by the pad, impeded airflow. Consequently, modifications were made to the pad's geometry and installation method.

The current configuration features the coconut coir pad positioned at the base of the wind catcher's opening. Further refinements led to the development of a sliding plate mechanism, incorporating a tilted coir-laden pad that does not fully obstruct the air intake, thereby facilitating unimpeded airflow while ensuring contact with the moistened coir. The pads are geometrically designed based on Bernoulli's principle, with their length increasing towards the interior opening, consequently reducing the aperture size at the base. This configuration ensures a greater air velocity as it passes through the constricted opening.

Following installation, a water supply pipe moisturizes the pads. Excess moisture from the upper pads gravitates onto the lower ones, ensuring consistent saturation across all pads. As ambient air enters the wind catcher, it flows over the pads, undergoes evaporative cooling, and subsequently enters the interior, rendering the space cooler than the external environment.

This prototype functions as an experimental apparatus for the practical observation of the cooling mechanism. Its design incorporates structural elements analogous to the camel's nasal passages, facilitating the examination of airflow, heat transfer, and moisture exchange within a controlled setting. The development phase ensures the translation of the biologically derived conceptual model into tangible engineering practice.

### 3.3 Thermodynamic and Performance Calculations

Following the experimental observations derived from the prototype, thermodynamic and performance calculations are undertaken. These calculations encompass the determination of cooling capacity, the measurement of temperature variations throughout the system, and the evaluation of energy exchange efficiency.(Pang et al., 2012) The quantitative data generated from these calculations serves to validate the prototype's performance and enables a comparative analysis against conventional cooling systems.

To theoretically calculate the interior temperature after installing the model, I have considered the hot arid region i.e. Kalburgi city in Karnataka for the study. The hottest months of the year 2023 i.e. 'March, April and May' are considered for calculation,To evaluate the performance of the camel-inspired cooling prototype, climatic data from the study region was categorized into temperature ranges. For each range, average dry-bulb temperature (T1T_1T1), relative humidity (RH), wet-bulb temperature (T3T_3T3), and humidity ratio (W1W_1W1) were recorded. The dataset is summarized in Table 1.

**Table 1:** Climatic Input Data for Calculations

| Temperature Range (°C) | Total Days | T1T_1 (°C) | RH (%) | T3T_3 (°C) | W1W_1 (kg/kg) |
|---|---|---|---|---|---|
| < 36 °C | 11 | 34.6 | 25 | 20.51 | 0.0086 |
| 36–38 °C | 23 | 36.5 | 27 | 22.45 | 0.0103 |
| 38–40 °C | 21 | 39.2 | 19 | 21.80 | 0.0084 |
| 40–43 °C | 36 | 40.4 | 28 | 25.60 | 0.0132 |

### 3.4 Analysis and Findings

The data acquired through the aforementioned calculations are subjected to systematic analysis to ascertain the efficiency of the camel-inspired cooling system. This analytical phase investigates whether the prototype achieves significant reductions in air temperature and if the employed process can be deemed energy-efficient. Furthermore, the findings are assessed for their scalability, exploring the potential for applying the system in practical building cooling scenarios. This analysis bridges the critical gap between biological inspiration, experimental design, and real-world applicability.

## 4. Results

### 4.1 Calculating the pad characteristics

Humid specific heat, calculated as the sum of the specific heat of dry air and the product of the humidity ratio (w1) and the specific heat of water vapor, is determined to be 1027 J/kg °C. This is based on the values Cpa = 1594 J/kg °C, w1 = 0.0137, and Cpv = 1868 J/kg °C(Bensafi et al., 2021; Heng et al., 2021). Concurrently, the volume of the cooling pad is computed using its dimensions: height (H) of 0.5m, width (W) of 0.5m, and length (l) of 0.1m, resulting in a volume of 0.025m$^3$.

The wetted surface area per unit volume of the cooling pad is established at 320m$^2$/m$^3$. Consequently, the total wetted surface area is calculated as the product of the pad volume and the surface area per unit volume, yielding 8 m$^2$. The characteristic dimension of the pad (lc) is then determined by dividing the pad volume by its total wetted surface area, resulting in 0.003125 m.

### 4.2 mass flow rate of air

Mass flow rate of air (ma) is computed as the product of air velocity (V), the density of the medium (ρ), and the surface area through which air passes(González & Salas, 2021). Wind velocities in Gulbarga during hot months range from 8 to 12 m/s; therefore, velocities of 8, 9, 10, 11, and 12 m/s were considered for the calculations. The volume flow rate is calculated using the formula Vf = ma / ρ, with the density of coconut coir taken as 1.12 kg/m$^3$. The inlet and outlet velocities of air are subsequently determined using Vi = Vf / Afi and Vo = Vf / Afo, respectively.

**Table 2:** Air velocity on coconut coir pad at different parameters

| | | | | | |
|---|---|---|---|---|---|
| Mass flow rate, ma (kg/s) | 2.28 | 2.56 | 2.85 | 3.13 | 3.42 |
| Volume flow rate, Vf (m3/s) | 2 | 2.25 | 2.5 | 2.75 | 3 |
| Inlet velocity, Vi (m/s) | 8 | 9 | 10 | 11 | 12 |

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| | | | | | |
|---|---|---|---|---|---|
| Outlet velocity, Vo (m/s) | 8 | 9 | 10 | 11 | 12 |
| Average velocity, Va (m/s) | 8 | 9 | 10 | 11 | 12 |

The characteristic length is utilized for the determination of the Reynolds and Nusselt numbers, where Nu = 0.10.120.80.33 and Pr = 0.71. The Reynolds number is calculated using the average velocity and characteristic length as Re = Va / v, with v (kinematic viscosity) equal to $1.460 \times 10^{-5}$. The heat transfer coefficient (h) is determined by dividing the Nusselt number by the characteristic length (lc), using a thermal conductivity (K) of 0.027 W/m°C. The saturation efficiency (η) of the cooling pad is calculated using the formula: η = 1 - exp[]. The leaving air temperature, which also represents the interior temperature (T2), is computed using the formula: T2 = T1 – η. The cooling capacity of the cooling pad is calculated as Qc = ma * 3.6 kJ/h.

**Table 3:** Performance parameters of coconut coir pad

| Velocity, V (m/s) | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|
| Mass flow rate, ma (kg/s) | 2.28 | 2.56 | 2.85 | 3.13 | 3.42 |
| Reynolds number, Re | 1712 | 1926 | 2140 | 2354 | 2568 |
| Nusselt number, Nu | 22.8 | 25 | 27.2 | 29.4 | 31.3 |
| Heat transfer coefficient, h | 196 | 215 | 234 | 253 | 271 |
| Saturation efficiency, η | 0.45 | 0.45 | 0.44 | 0.42 | 0.4 |
| Leaving temperature, T2 (0C) | **33.7** | **33.7** | **33.9** | **34** | **34.4** |
| Cooling capacity, Qc (kJ/h) | **54.9** | **61.74** | **66.69** | **72.1** | **73.8** |

## 5. Discussion

The performance evaluation of the coconut coir pad underscores the critical interdependence among air velocity, mass flow rate, and overall cooling effectiveness.

**Reynolds Number:** The calculated Reynolds numbers fall within the laminar-transitional range, indicating that the airflow through the coir pad is predominantly smooth, with incipient turbulence observed at elevated velocities. This flow regime suggests a relatively uniform air distribution, which is conducive to efficient heat and mass transfer across the pad's surface.

**Nusselt Number:** A positive correlation between the Nusselt number and increasing velocity is observed, signifying enhanced convective heat transfer. Although higher velocities promote greater heat transfer due to intensified air-water interaction, they concurrently reduce the contact duration between the air and the saturated medium.

**Heat Transfer Coefficient:** The heat transfer coefficient demonstrates a consistent augmentation with increasing velocity, directly correlating the intensity of air movement with the rate of heat exchange. This observation reinforces the principle that augmented airflow elevates the capacity for sensible heat transfer, thereby improving the pad's capability to remove heat from the incoming air.

**Saturation Efficiency:** A discernible decline in saturation efficiency is noted as the air velocity escalates. This phenomenon is attributable to the reduced residence time of air in contact with the moistened coir fibers at higher flow rates, which impedes the efficacy of evaporative cooling. Maximum efficiency is achieved at lower velocities, where the interaction between air and water is optimized.

**Leaving Air Temperature:** The temperature of the air exiting the pad exhibits a gradual increase with rising velocity, consistent with the diminishing efficiency observed at higher flow rates. Although the pad provides substantial cooling at lower velocities, its performance experiences a slight degradation at increased air throughputs due to incomplete air saturation.

**Cooling Capacity:** Notwithstanding a reduction in saturation efficiency, the overall cooling capacity increases with higher airflow rates. This effect is primarily driven by the elevated mass flow rate of air. The results indicate a trade-off wherein greater air volumes yield higher total cooling output, even at a decreased

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per-unit efficiency. The selection of an optimal operating condition is contingent upon whether the system design prioritizes peak efficiency or maximum cooling load capacity.
It can be summarized that at low velocity, it yields higher efficiency and a lower cooling load, making it suitable for applications prioritizing energy savings and comfort cooling. At higher velocities, it results in a greater cooling capacity but reduced efficiency, which is advantageous for large spaces with substantial cooling demands where airflow is paramount. Hence, the coconut coir pad demonstrates moderate efficiency and significant cooling potential, presenting itself as an economical and sustainable substitute for conventional evaporative pads.

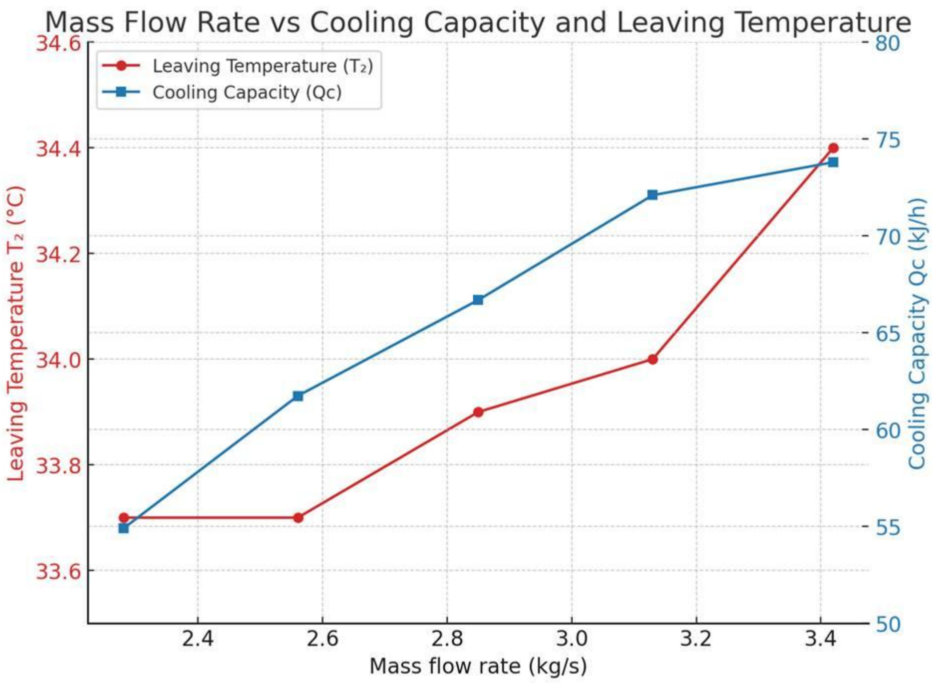


**Figure 1: dual-axis graph representing mass flow rate vs cooling capacity and leaving temperature together**

The dual-axis plot of leaving temperature and cooling capacity against mass flow rate highlights the inherent trade-off in the performance of the coconut coir pad. As the mass flow rate increases, the cooling capacity rises substantially (from 54.9 to 73.8 kJ/h), indicating greater total heat removal. However, this is accompanied by a gradual increase in the leaving air temperature (from 33.7 °C to 34.4 °C), reflecting a decline in evaporative effectiveness due to reduced air–water contact time at higher flow rates. Thus, while higher mass flow rates favor bulk cooling demand, lower flow rates yield cooler supply air and greater saturation efficiency. This balance must be considered in selecting optimal operating conditions based on whether efficiency or capacity is prioritized.

## 6. Conclusion

The developed prototype, inspired by the thermoregulatory mechanism of the camel's nasal cavity, successfully demonstrates the potential of coconut coir as an effective evaporative cooling medium. The performance analysis shows that the system can achieve a cooling capacity in the range of 54.9–73.8 kJ/h, with leaving air temperatures between 33.7 °C and 34.4 °C under varying mass flow rates. Although saturation efficiency decreases slightly with increasing airflow, the prototype consistently delivers meaningful cooling, balancing efficiency and capacity. These results confirm that the prototype can contribute to reducing indoor thermal loads in hot and dry climates, offering a low-cost, eco-friendly, and locally available alternative to conventional evaporative cooling materials. Overall, the study validates both the design concept and the performance feasibility of the prototype, establishing a foundation for further scaling and optimization.

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