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Smart Rooftop Cooling and Ventilation System

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Abstract

Rooftop heat accumulation in tropical climates, such as Malaysia, frequently results in significant indoor thermal discomfort. Conventional cooling methods, including air conditioning and passive ventilation, are often energy-inefficient and lack the adaptability required to respond to dynamic climatic conditions. To address this, the study presents a Smart Rooftop Cooling and Ventilation System designed to optimize indoor airflow and temperature regulation through predictive automation. The system integrates an ESP32 microcontroller, exhaust fans, mist sprayers, and environmental sensors with a Multiple Linear Regression (MLR) machine learning model. Results indicate that the system effectively demonstrated the responsiveness of the cooling and safety logic through simulated environmental conditions. The predictive mechanism successfully reduced rooftop temperatures and stabilized ambient conditions. Furthermore, the system incorporates smart energy management by modulating fan speeds upon reaching target temperatures and includes a rain detection safety interrupt. This solution successfully combines embedded engineering and Internet of Things (IoT) to provide a cost-effective approach to residential thermal comfort.

1. Introduction

Predictive analytics, integrated with communication technologies and embedded systems, has driven remarkable innovations in intelligent solutions for smart homes [1]. These technologies address critical issues associated with real-time environmental monitoring, adaptive control, and predictive decision-making within building management systems.

The tropical climate in Malaysia leads to significant heat accumulation in residential rooftops, where daily temperatures typically range between 30.6˚C and 32.4˚C [2]. Conventional cooling methods often rely on static set-points and lack flexibility [3], resulting in excessive energy consumption. Consequently, systems capable of proactively regulating temperature and humidity based on dynamic environmental conditions are urgently required.

Indoor thermal discomfort is a major challenge in residential buildings due to prolonged exposure to elevated roof temperatures [4]. Existing air conditioning units and passive exhaust fans are often inefficient as they operate reactively rather than dynamically. A critical limitation of current rooftop control systems is the absence of predictive control using machine learning, which is essential for adaptive learning and automated future-state projections to optimize performance.

Recent research has examined the use of IoT in automated misting systems for agriculture, providing evidence that supports the efficacy of evaporative cooling [5]. Unlike traditional control systems, these studies highlight the importance of human-in-the-loop automation and predictive algorithms to enhance HVAC energy efficiency and occupant comfort [6]. Similar applications in the region, such as smart rooftop farming systems in Brunei, have successfully utilized mobile applications for monitoring; however, these systems generally lack the predictive control capabilities proposed in this application [7].

Poor indoor air quality and thermal discomfort in low-income tropical housing pose potential health hazards to occupants, necessitating improved approaches to natural ventilation [8]. Recent hardware advancements in HVAC systems increasingly leverage smart computing to optimize energy consumption and operational flexibility [9]. Literature indicates that evaporative cooling with water misting is effective for cooling outdoor and semi-outdoor environments, offering a sustainable alternative to energy-intensive air conditioning [10]. To enhance responsiveness, remote monitoring and control based on real-time environmental data are critical, justifying the integration of IoT technologies into exhaust fan systems [11].

This research aims to achieve the following objectives: (1) To develop a smart cooling and ventilation system utilizing an ESP32 microcontroller and environmental sensors; (2) To apply a Multiple Linear Regression (MLR) framework for temperature pattern prediction to proactively activate cooling devices; and (3) To validate the stability and responsiveness of the system under simulated temperature and humidity conditions.

2. Methodology

The development of the Smart Rooftop Cooling and Ventilation System aims to deliver an autonomous and predictive thermal control solution. The methodology is structured into three primary phases: system architecture design, hardware implementation, and the development of the predictive control logic.

2.1 System Architecture

The system functions as a closed-loop control mechanism, processing environmental data to regulate active cooling interventions. As illustrated in Figure 1, the architecture is categorized into three fundamental stages: Input, Process, and Output. The Input Stage is responsible for data acquisition, collecting real-time environmental parameters such as temperature, humidity, and rain status using high-precision sensors. This data is then transmitted to the Process Stage, where the core processing unit, an ESP32 microcontroller integrated with a Multiple Linear Regression (MLR) algorithm, analyzes the input to forecast future temperature trends and determine the necessary control actions. Finally, the Output Stage executes these decisions by activating the cooling components, specifically variable-speed exhaust fans and mist sprayers, or by triggering safety mechanisms to protect the system during adverse weather conditions.

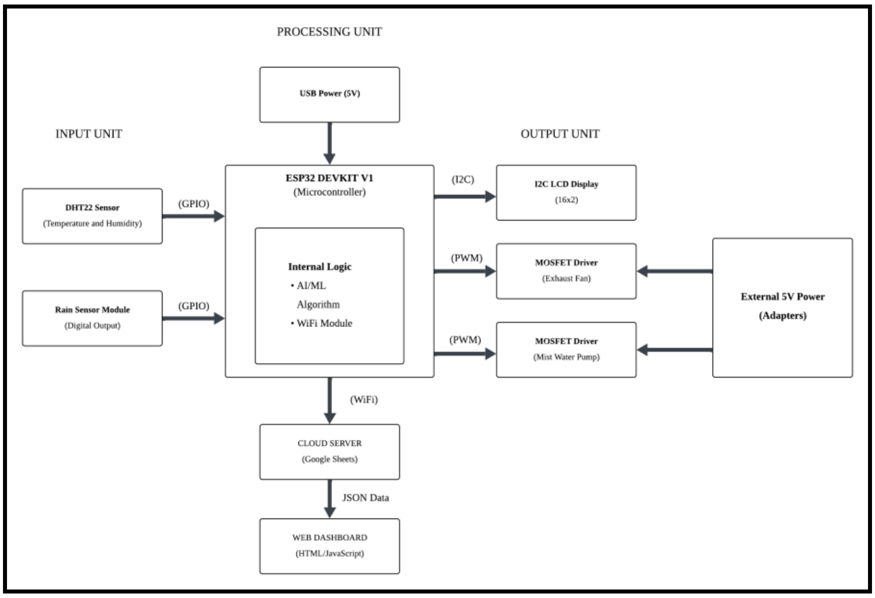

Fig.1 *Project Block Diagram*

2.2 Hardware Implementation

The system hardware was developed as a functional prototype designed to operate within a controlled testbed that simulates tropical environmental conditions. The ESP32 microcontroller serves as the central processing unit, selected for its dual-core architecture and built-in Wi-Fi capabilities, which facilitate seamless data logging during the simulation.

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To monitor the variable conditions, the system utilizes a DHT22 sensor to measure temperature and humidity changes. To replicate high-temperature scenarios, an external heat source was applied to the sensor environment, allowing the system to validate its response to rapid thermal spikes. Additionally, a Rain Sensor Module is integrated to detect simulated precipitation, triggering an immediate system interrupt to isolate power and prevent potential electrical damage.

For actuation, the system employs 5V DC exhaust fans to facilitate active ventilation and a micro submersible water pump to drive the evaporative misting unit. Since the ESP32 operates on a 3.3V logic level, IRLZ44N MOSFETs are utilized as logic-level switches. This configuration ensures that the low-voltage controller can efficiently and safely drive the high-power actuators in response to the simulated environmental stressors.

2.3 Predictive Model Development

To govern the automated operation of the cooling components, a Multiple Linear Regression (MLR) model was developed. This model was trained using a historical dataset of environmental parameters to establish correlations between current atmospheric conditions and future temperature trends. The specific predictive equation derived from the training phase is represented by Equation (1):

$$T\_predicted = 2.39 + (0.89 \times T\_actual) + (0.012 \times H\_actual) \quad \text{(Equation/Eq.1)}$$

Where:

- T_predicted= Predicted Future Temperature (˚C)
- T_actual = Current Ambient Temperature (˚C)
- H_actual = Current Relative Humidity (%)
- 2.39 = Y-intercept (Bias)
- 0.89 = Temperature Weight Coefficient
- 0.012 = Humidity Weight Coefficient

These regression coefficients were embedded directly into the ESP32 firmware. This allows the microcontroller to compute the predicted temperature in real-time without requiring constant external processing.

The control logic dictates that if T_predicted exceeds the critical threshold of 33.0˚C, the cooling system activates preemptively. This proactive approach ensures that the environment is cooled before reaching uncomfortable or damaging heat levels, significantly enhancing system efficiency compared to reactive methods.

2.4 System Flowchart

The operational logic of the firmware is illustrated in Figure 2, detailing the complete sequence from system initialization to actuation and data logging. Upon startup, the ESP32 initializes the input/output pins, synchronizes with real-time internet time servers, and verifies the Wi-Fi connection. Once connectivity is established, the system enters its main control loop by acquiring real-time environmental data from the DHT22 and rain sensors. If the sensor readings are validated, the firmware proceeds to compute the predictive temperature using the embedded Multiple Linear Regression (MLR) formula.

The core decision-making process is governed by a strict hierarchy of control priorities to ensure safety and efficiency. The highest priority, defined as Priority 1 (Safety Mode), is triggered if the rain sensor detects precipitation. In this state, the logic immediately overrides all other controls, setting the fan speed to zero and entering "Rain Mode" to prevent hardware damage. In the absence of rain, the system evaluates Priority 2 (Predictive Pre-Cooling), comparing the MLR-predicted temperature against the critical threshold. If the prediction exceeds the set limit, the system proactively drives the exhaust fans at maximum speed (PWM 255) to dissipate heat. If neither condition is met, the system operates under Priority 3 (Normal Operation), where fan speed is modulated using a linear PWM logic proportional to the current ambient temperature.

Following the ventilation control, the system assesses the criteria for the misting subsystem. The mist pump is activated only if specific environmental conditions are satisfied. Specifically when the ambient temperature exceeds 33°C and the relative humidity is below 80%. The final stage of the cycle involves updating the LCD interface with current status information and verifying the data upload timer. Once the 60-second interval is reached, the system transmits the logged data to the Google Sheets cloud server before repeating the control loop.

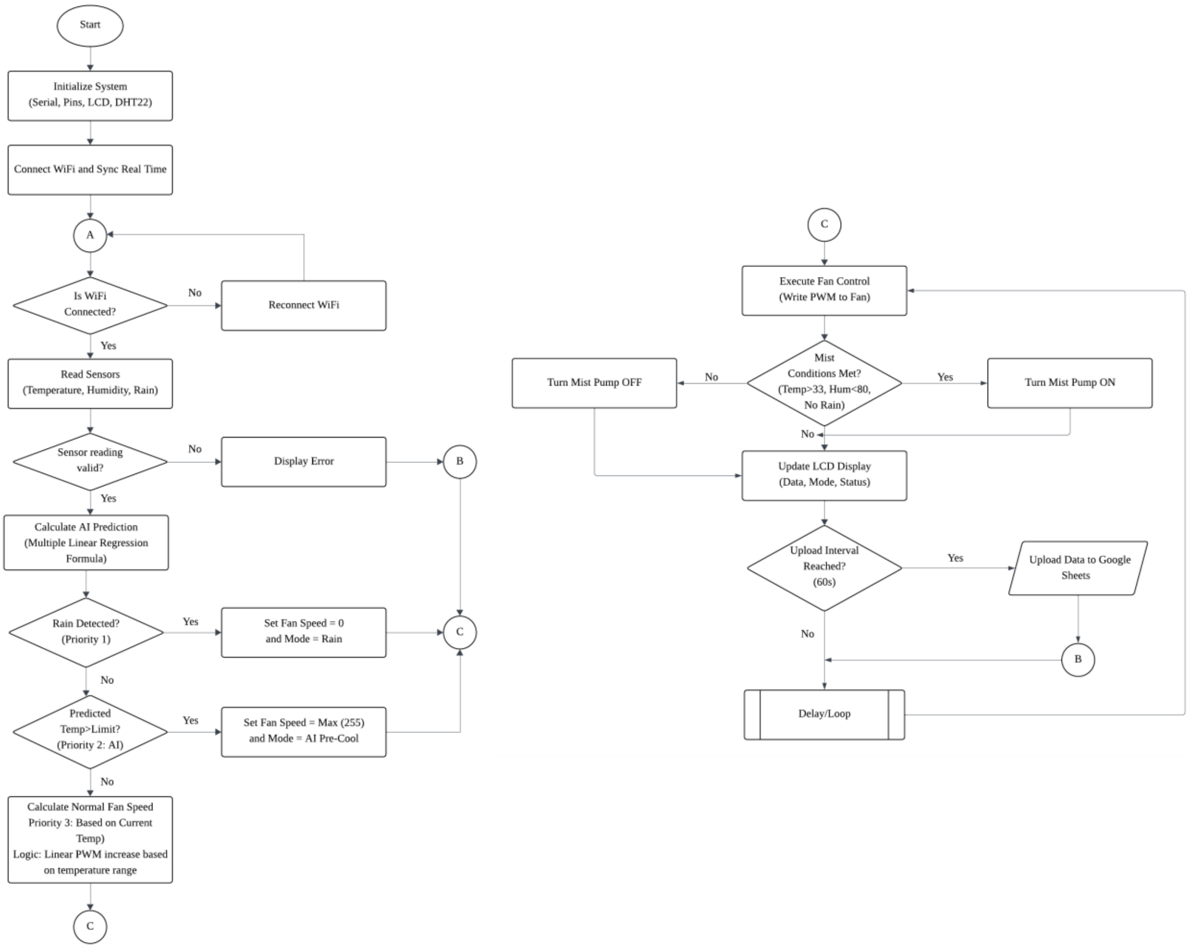


Fig. 2 *System Flowchart*

3. Result and Analysis

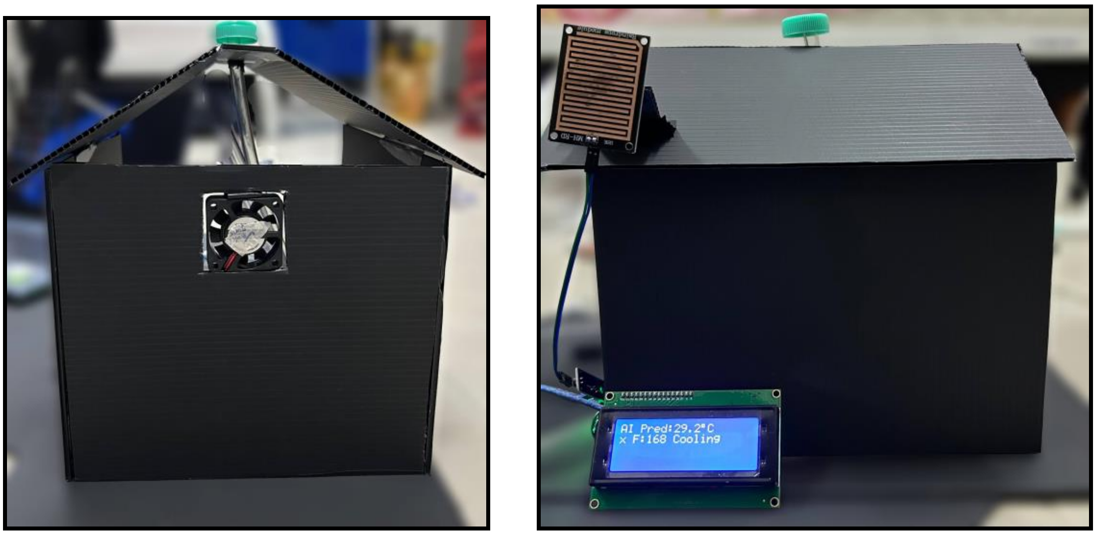
This section presents the data obtained from the hardware integration process, the statistical validation of the predictive control logic, and the quantitative assessment of the system's cooling performance. The analysis specifically evaluates how the system operates under simulated tropical environmental conditions to validate the proposed system architecture

3.1 Implementation of Hardware Prototype

The prototype of the Smart Rooftop Cooling System is illustrated in Figure 3. The prototype structure was fabricated using black corrugated polypropylene sheets, a material selected to emulate the high thermal absorption and retention properties of standard asphalt or metal roofing. This "black box" design serves as the controlled testbed for the simulation.

As observed in the figure, the hardware integration is compact and functional. The Rain Sensor Module is mounted on the inclined roof surface to ensure immediate detection of simulated precipitation. For active ventilation, a 5V DC Exhaust Fan is embedded in the lateral wall to extract trapped heat. The system interface is provided by an I2C LCD screen positioned at the base. In the image, the LCD confirms the active execution of the predictive algorithm, displaying the "AI Pred" (Predicted Temperature) at 29.2°C and the current fan status

(F:168 Cooling), which corresponds to the Pulse Width Modulation (PWM) signal driving the fan speed. This visual evidence confirms that the microcontroller is successfully processing input data and driving actuators in real-time.



(a) (b)

Fig. 3 *Prototype of AI-Driven Smart Rooftop Cooling System (a) Side View; (b) Front View*

3.2 Accuracy of Machine Learning Model

The efficiency of the control system relies fundamentally on the Multiple Linear Regression (MLR) algorithm used to forecast thermal trends. To validate this model, the system's Predicted Temperature output was logged and compared against the Actual Temperature recorded by the DHT22 sensor. The correlation between these two datasets is visualized in Figure 4.

The graph plots the temperature data over a testing period from 17:15 to 21:00. The Red Solid Line represents the actual ambient temperature measured by the sensor, while the Blue Dashed Line represents the value forecasted by the MLR algorithm. As observed, the system successfully anticipated rapid thermal changes, specifically during the sharp temperature spikes at 17:30 and 18:00 (simulated heat events). The predicted values follow the actual temperature trajectory with high fidelity, maintaining a mean deviation of less than ±0.5°C. This tight correlation confirms that the regression coefficients embedded in the firmware are mathematically valid and capable of accurately predicting thermal behavior in this environment.

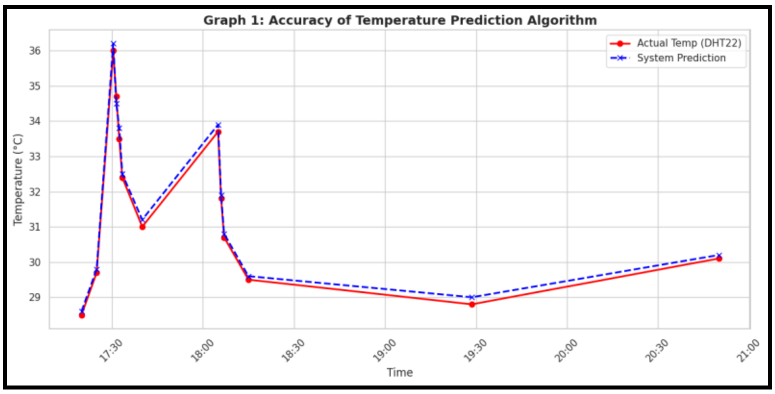


Fig. 4 *Comparison between MLR Predicted (Blue) with Actual Sensor Readings of Temperature (Red)*

3.3 Cooling Performance and Thermal Stability

The system's dynamic response to thermal stress was evaluated by inducing a sudden heat load to simulate a peak tropical afternoon. The interaction between the ambient temperature, fan speed, and misting activation is visualized in Figure 5, which plots the Temperature (˚C) on the primary y-axis (Red Line) and the Fan Speed (PWM) on the secondary y-axis (Green Dashed Line).

As observed at the 17:30 mark, the ambient temperature spiked sharply to 36˚C due to the simulated heat event. In response, the predictive algorithm correctly identified the critical threshold breach (33˚C) and immediately triggered the Mist Activation (indicated by the Blue Star) while ramping the Fan Speed to its maximum duty cycle (PWM 255). This combined active cooling mechanism, utilizing both ventilation and evaporative misting, resulted in an immediate and steep drop in temperature, reducing the internal heat from 36˚C down to approximately 31˚C within a short interval.

The most critical observation regarding energy efficiency occurs after the 18:00 mark. As the temperature stabilized back to the comfort range (~29˚C), the system did not maintain maximum power consumption. Instead, the Green Line demonstrates that the fan speed automatically decreased to a lower PWM value in direct correlation with the dropping temperature. This inverse relationship validates the effectiveness of the energy-saving algorithm, confirming that the system intelligently conserves power by only applying the necessary amount of cooling required to maintain thermal stability.

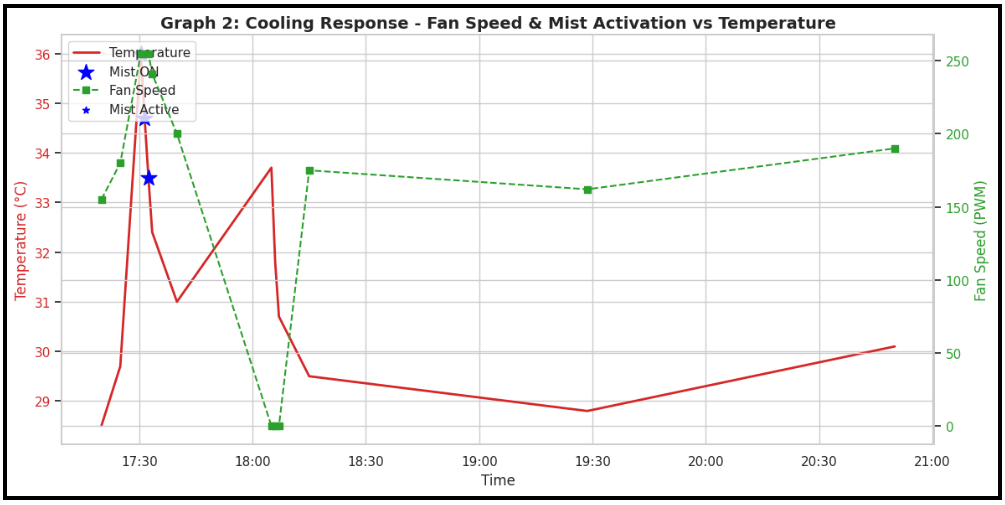


Fig. 5 *Cooling Response - Fan Speed (Green) & Mist Activation (Blue Star) vs. Temperature (Red)*

4. Discussion

4.1 Interpretation of Findings

The findings demonstrate that rooftop cooling efficiency is significantly enhanced through the integration of the Multiple Linear Regression (MLR) model. Unlike traditional thermostat-based systems, which operate on a purely reactive basis and active only after a temperature spike has occurred, the proposed system utilizes a predictive approach. By anticipating heat accumulation before it reaches critical levels, the system initiates the misting and ventilation process preemptively. This ensures that the internal environment remains within the thermal comfort zone while utilizing less overall energy compared to continuous operation. Furthermore, the successful execution of the rain safety interrupt confirms the system's practicality for tropical climates, ensuring that the electronic components are protected from moisture damage, thereby extending the operational lifespan of the hardware.

4.1 Comparison with Existing Solutions

Current residential cooling solutions typically fall into two categories: passive ventilation or high-energy active cooling. Passive systems, such as wind-driven turbine vents, are energy-efficient but often fail to provide adequate cooling during peak solar radiation hours. Conversely, air conditioning provides superior comfort but incurs high operational costs and energy consumption. This research bridges the gap between these two extremes by offering a solution that is active, automated, and significantly more energy-efficient than full air conditioning. The successful implementation of the ESP32 microcontroller and low-cost sensors confirms that smart building technology can be cost-effective, making it a viable option for residential retrofitting where budget constraints are a primary concern.

5. Conclusion

5.1 Overview of Achievements

This project successfully developed and validated a predictive smart cooling and ventilation system designed specifically for rooftop applications. The primary objective of maximizing indoor thermal comfort was achieved through the application of a predictive control algorithm embedded within the ESP32 firmware. Experimental results confirmed the system's ability to rapidly reduce ambient temperatures from above 36°C to comfortable levels within minutes. Additionally, the robustness of the system was ensured through the integration of a rain sensor, making it suitable for the unpredictable weather patterns characteristic of the Malaysian tropical climate. The prototype serves as a confirmation that integrating IoT sensors with embedded machine learning is a practical, cost-efficient, and sustainable approach to modern building management.

5.2 Future Work Recommendations

While the current prototype functions effectively within the testbed environment, several enhancements could further optimize its real-world application. A significant recommendation for future work is the integration of a Solar Photovoltaic (PV) power supply. Given that the system is roof-mounted, harnessing solar energy would render the unit fully self-sustaining and off-grid, eliminating the need for external power sources. Furthermore, user accessibility could be improved through the development of a dedicated mobile application using platforms such as Blynk or MIT App Inventor. This would enable users to monitor real-time temperature data remotely and manually adjust threshold settings, thereby enhancing the overall user experience and system flexibility.

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References

[1] Statista. (2024, March). *Smart Home - Worldwide*. Statista Market Forecast. https://www.statista.com/outlook/cmo/smart-home/worldwide

[2] Muhamad, & Lim, C. H. (2024). Thermal Performance of Residential Roofs in Malaysia: Experimental Study Using an Indoor Solar Simulator. *Buildings, 14*(1), 178. https://doi.org/10.3390/buildings14010178

[3] Nimmala, K., Ramasamy, K., & Ramireddy, L. (2024). Smart Home Automation and Monitoring System Using ESP32 Microcontroller. *Proceedings of the 2024 International Conference on Electronics, Computing and Communication Technologies (CONECCT)*, 1–6.

[4] Azzmi, N. M., & Jamaludin, N. (2014). A Review of Heat Transfer in Terraced Houses of Tropical Climate. *E3S Web of Conferences, 3*, 01010. https://doi.org/10.1051/e3sconf/20140301010

[5] Resquites, R. S., Velasco, J. A., & De Leon, M. T. (2023). IoT-Based Automated Misting System for Urban Farming. *2023 IEEE 15th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM)*, 1–5. https://doi.org/10.1109/HNICEM59187.2023.10398012

[6] Liang, X., & Say, B. (2025). Human-in-the-loop AI for HVAC management enhancing comfort and energy efficiency. *arXiv*. https://doi.org/10.48550/arXiv.2505.05796

[7] Nur, Ravi Kumar Patchmuthu, & Wida. (2023). Smart Rooftop Farming Using IoT and Mobile Application in Brunei. *2022 IEEE International Conference on Artificial Intelligence in Engineering and Technology (IICAIET)*, 164–169. https://doi.org/10.1109/iicaiet59451.2023.10291903

[8] Kajjoba, D., et al. (2024). Impact of natural ventilation and outdoor environment on indoor air quality and occupant health in low-income tropical housing. *Energy Reports*, 12, 4184–4194. https://doi.org/10.1016/j.egyr.2024.10.004

[9] Lee, D., & Lee, S.-T. (2023). Artificial intelligence enabled energy-efficient heating, ventilation and air conditioning system: Design, analysis and necessary hardware upgrades. *Applied Thermal Engineering*, 235, 121253. https://doi.org/10.1016/j.applthermaleng.2023.121253

[10] Ulpiani, G. (2019). Water mist spray for outdoor cooling: A systematic review of technologies, methods and impacts. *Applied Energy*, 254, 113647. https://doi.org/10.1016/j.apenergy.2019.113647

[11] A, N., Alagari, L., & Lias, J. (2021). IoT based Smart Exhaust Fan. *Evolution in Electrical and Electronic Engineering*, 2(2), 47–56. https://publisher.uthm.edu.my/periodicals/index.php/eeee/article/view/4190