

The efficiency of the smart sterilised ventilation system in residential bathrooms in Taiwan.

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ABSTRACT

Due to limited residential space in Taiwan, bathrooms and toilets are often integrated into a single area, resulting in excessive humidity and organic residue that encourage bacterial and fungal growth. This study develops an intelligent ventilation system with sterilisation capabilities to address this issue. The system uses infrared (IR) lamps to raise the ambient temperature and increase the saturated vapour pressure, evaporating condensation from ceilings and walls. Simultaneously, ultraviolet (UV) lamps are activated to sterilise airborne microbes via induced air turbulence. For safety, UV lamps only operate when no human presence is detected, based on infrared sensors. The system automatically activates or deactivates ventilation fans based on absolute humidity thresholds (0.015 kg/kg' and 0.021 kg/kg'), and triggers all components, including the IR lamp and UV unit, when the ambient temperature falls below 29°C. This approach maintains an optimal indoor temperature and humidity while improving the air quality.

KEYWORDS bathroom, moisture, colony-forming units (CFUs), smart sterilised ventilation system

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1. Introduction

Due to limited interior residential space in Taiwan, many bathrooms are located in poorly ventilated areas, leading to long-term humidity and darkness that create the ideal conditions for mould and fungal growth, which can negatively impact indoor air quality and occupant health (Lee, 2017). The use of hot water for showers or bathing raises both the temperature and relative humidity. Without effective exhaust systems, moisture accumulates, and organic matter, such as hair, towels, and construction materials, serves as nutrients for mould. In such oxygen-rich, humid environments (e.g., 25°C and 95% RH), fungi flourish, posing a risk for respiratory illnesses (Ji, 2003).

The warm and humid climate in Taiwan further encourages fungal growth and airborne spore transmission (Chu, 2009). When the indoor relative humidity exceeds 75% for extended periods, common fungi such as *Aspergillus* and *Cladosporium* grow rapidly, especially in difficult-to-clean areas like ceilings and wall corners (Tseng, 2021). These fungi produce stable pigments (red, black, blue, white) that deeply adhere to surfaces and are difficult to remove. Airborne spores are major contributors to asthma, liver disease, and allergic reactions (Ji, 2003).

Poor airflow and ineffective ventilation in bathrooms often cause moisture to build up, damaging electronics and construction materials and increasing biological contaminants in indoor air. This can lead to allergies and upper respiratory symptoms. A field survey of 32 residential bathrooms found that many lacked windows and did not have functional exhaust fans, as shown in Figure 1. Over half of the installed fans were not properly ducted, causing

long-term moisture retention above ceiling panels, which promotes microbial and bacterial growth, as shown in Figure 2 (Lee, 2018).

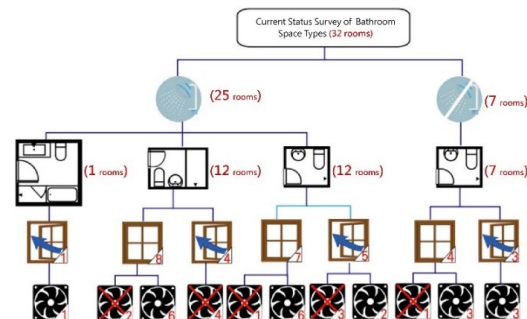


Figure 1. Current status survey of bathroom space types.



Figure 2. Microbial and bacterial growth in the ceiling.

Bathing or showering with hot water in bathrooms raises the indoor temperature and causes significant evaporation, which in turn increases the relative humidity. In poorly ventilated bathrooms, this moisture becomes trapped, leading to prolonged dampness. At ambient temperature, air naturally contains varying amounts of water vapour depending on the room's function. For instance, a single bathtub can generate 500–1000 g/h of steam (Architectural Institute of Japan, 1988).

When hot water is used, water vapour saturates the air, and if the surrounding temperature drops, the vapour condenses easily forming droplets on ceilings, walls, and floors. If surface materials are not absorbent, this moisture promotes mould growth. Bathrooms, with their limited airflow and frequent condensation, are a prime example of such an environment.

Lee et al. (2018) noted that trapped bathroom humidity often spreads to adjacent rooms, making en-suite layouts potentially unhealthy. Similarly, Li (2001) emphasised that maintaining dryness and airflow is essential to prevent microbial growth. In non-air-conditioned buildings, natural ventilation is often used to regulate indoor temperature, humidity, and airflow paths to improve occupant comfort (Yang, 2005).

With the rapid development of sensing technologies, cloud computing, and AI, the Internet of Things (IoT) has enabled more intelligent environmental control. IoT systems consist of embedded sensors, microcontrollers (MCUs), gateways, and end-user devices. Machine-to-Machine (M2M) communication is a fundamental aspect of IoT, allowing devices to exchange data autonomously. Given the energy and processing limitations of MCUs, M2M protocols must be optimised for low power consumption, low latency, and high reliability. Quality of Service (QoS) settings are also essential to ensure timely and accurate data transmission (Corocoran, 2016).

In this study, IoT technologies are applied to bathroom environments to manage humidity and inhibit microbial growth. Environmental conditions are monitored using sensor modules and transmitted through secure gateways. The collected data are analysed and integrated into control algorithms, which then trigger dehumidification and sterilisation actions, ensuring responsive and effective environmental management.

2. Methodology

To address common issues of humidity and poor ventilation in bathrooms, this study deployed sensors to monitor temperature and humidity in real time. Data were transmitted to the cloud for analysis, enabling the system to maintain environmental conditions within a defined optimal range. Based on this analysis, appropriate devices, such as fans, heaters, and UV lamps, were activated automatically for ventilation, drying, and sterilisation.

Contrary to popular belief, preliminary sampling revealed that the most mould-prone areas were not near the drain but rather at the edges of ceilings and floor corners where moisture tends to accumulate due to stagnant airflow. To verify this, temperature and humidity sensors were installed at three indoor positions and one outdoor reference point for long-term monitoring, as shown in Figure 3 (Lee et al., 2018). The outdoor sensor helped capture ambient changes and their influence on indoor conditions. During showering, measurement points 2 and 3 inside the bathroom were found to reflect the most significant changes in humidity, identifying them as critical monitoring locations, as shown in Figure 4.

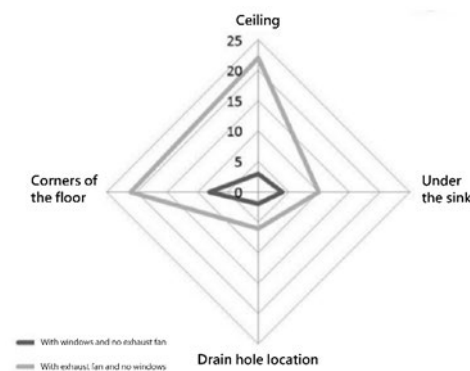


Figure 3. Locations in bathroom spaces where fungi are likely to breed.

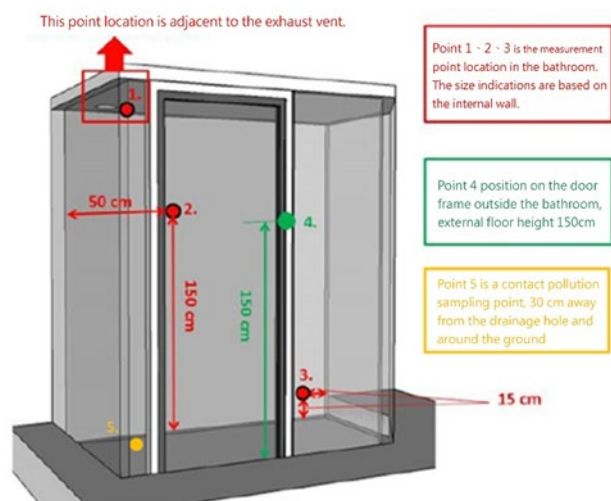


Figure 4. Bathroom measuring point and the locations.

During a typical shower, hot water produces steam that rises and accumulates near the ceiling. Mechanical ventilation using exhaust fans is commonly employed to extract this moisture and maintain a dry environment. In this study, three HOBO temperature and humidity data loggers were installed at different vertical locations, such as ceiling (I1), 150 cm above the floor (I2), and 15 cm above the floor (I3), to record ambient conditions at one-minute

intervals (Table 1, A-1). A multifunctional reference-grade instrument (A-2) was also used to measure airflow velocity and volume at air inlets and outlets, providing essential parameters for triggering IoT-controlled ventilation and sterilisation equipment.

To assess fungal contamination, surface samples were collected using sterile swabs (B-1) at location I5. Each swab was immersed in 1 mL of sterile fluid and inoculated onto a total viable count test strip (B-2), which was then incubated at 35°C for 24 hours before evaluation. For airborne microbial sampling, a bioaerosol collector (B-3) was used to draw 100 litres of air over one minute onto an agar plate (B-4). The plates were sealed and incubated at 30°C for 24 hours to determine colony-forming unit (CFU) concentrations in the air. These results served as baseline data to evaluate the effectiveness of the sterilisation system.

This study aimed to investigate the ventilation performance in bathroom environments through field experimentation. Based on the findings of Chang (2022) and Chen (2024), the integration of IoT sensors with cloud-based analytics in residential bathrooms enables effective monitoring of temperature, humidity, and mould concentration. Their study confirmed that IoT systems are capable of promptly detecting moisture accumulation even in compact spaces, significantly reducing biological hazards caused by excessive humidity.

To guide system design, ventilation rates were calculated to determine the required airflow, air velocity, and opening area using Equation (1).

$$Q = ACH \cdot V = A \cdot v \tag{1}$$

where Q = ventilation volume entering the room per hour (m^3/h), ACH = air exchange per hour (h^{-1}), V = room volume (m^3), A = ventilation outlet area (m^2), v = wind speed (m/h).






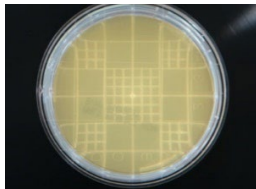
According to previous studies, mould tends to grow most rapidly at temperatures between 15°C and 30°C and relative humidity (RH) levels of 75% to 95% (Ji, 2003). Based on this, the proposed IoT system was initially configured to use RH as the primary parameter for fan control. Thresholds of 90% and 65% RH were set to trigger fan activation and deactivation, respectively. Field tests were conducted to validate this strategy and refine the control logic accordingly.

During a 6-hour test, showering with hot water caused RH to rise rapidly above 90%, triggering full-speed fan operation. The fan remained active until the RH dropped to 65%, which typically took about 18 minutes. However, relying solely on RH for fan control proved unreliable—leading to premature shutdowns and insufficient dehumidification. To address this, absolute humidity (AH) was calculated using operating temperature and RH measurements for more accurate environmental assessment, as per Equation (2).

$$AH = \frac{6.112 \times e^{\frac{17.67T}{T+243.5}} \times rh \times 2.1674}{273.15 + T} \tag{2}$$

where T = Temperature in degree Celsius (°C),
 rh = Relative humidity as a percentage (%)
 e = Euler’s number (mathematical constant ≈ 2.71828).

Table 1. Physical quantity measurement and fine fungi sampling equipment in this study.

A. Physical measurement		B. Delicate fungal sampling	
Temperature and humidity	Wind speed/air volume	Contact source of pollution	Air pollution sources
1. HOBO temperature and humidity loggers	2. Intelligent multi-function measuring	1. Colony-forming units Sampling stick	3. Bioaerosol Sampling
			
Air temperature (°C), relative humidity (%), dew point temperature (°C)	Wind speed (m/s), air volume (m³/h), temperature (°C), relative humidity (%)	2. Colony-forming units sampling paper	4. Petri dish
			

Absolute humidity (AH) refers to the amount of water vapour present in each volume of air, specifically the water vapour density, typically expressed in units of g/m^3 . The water content in the air (in $kg/kg\text{-air}$ or kg/kg') can be calculated based on the air temperature (T) and relative humidity (RH). Under normal atmospheric conditions, the behaviour of water vapour in air approximates to that of an ideal gas. Using the ideal gas law ($PV = nRT$), the formula for absolute humidity can be derived. Based on the 6-hour experimental results, the changes in absolute humidity were calculated from the temperature and relative humidity measurements, as shown in Figure 5. The data reveal that, after the fan system ceased operation, the water content in the bathroom initially decreased. However, due to the influence of outdoor environmental conditions through ventilation openings, the water content in the bathroom showed no significant reduction over the 6-hour period and remained consistently higher than the outdoor humidity.

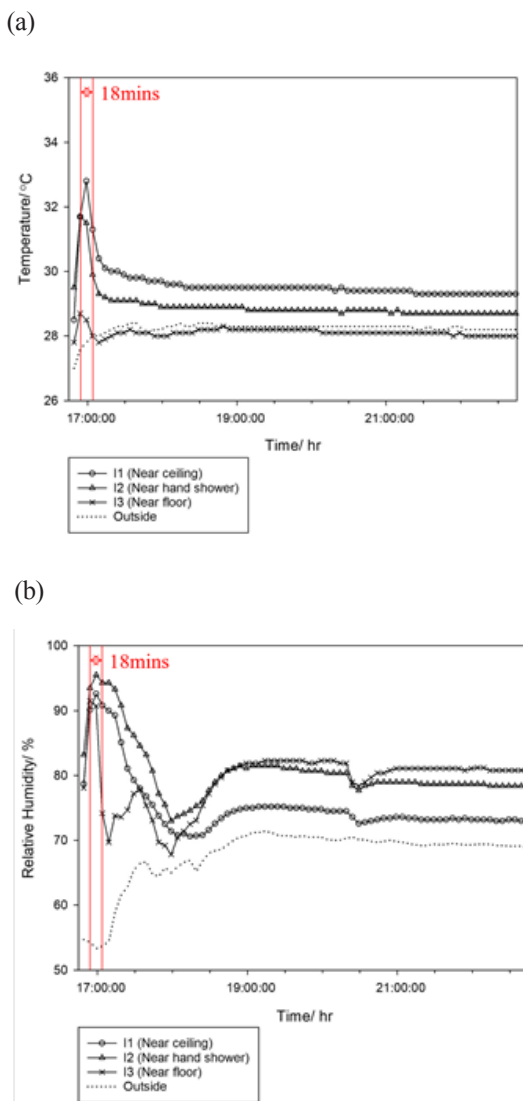


Figure 5. (a) Experimental temperature; and (b) absolute humidity changes.

Based on the humid subtropical climate in Taiwan, where average summer temperatures reach $28\text{--}29^\circ\text{C}$ and winter temperatures fall below 20°C , an optimal indoor air velocity of $0.5\text{--}1.0\text{ m/s}$ corresponds to a target absolute humidity (AH) range of $14\text{--}17\text{ g/kg'}$ (or $0.014\text{--}0.017\text{ kg/kg'}$). It is mainly related to the temperature of the bathroom after showering. The hot water used for showering in Taiwan is usually between 38 and 40°C . Therefore, when the temperature drops to 29°C , the water droplets attached to the wall or the ground are more difficult to evaporate. Therefore, the space needs to be heated to evaporate the water droplets into the form of water vapour. Taking into account seasonal temperature variations and the trade-off between fan operation time and energy consumption, this study set two key reference AH thresholds, 0.021 kg/kg' and 0.015 kg/kg' , along with corresponding temperature setpoints at 29°C and 32°C . These thresholds were used for cloud-based analysis and sensor-driven automation in subsequent experiments.

To implement the IoT-based monitoring and control system, Arduino microcontrollers were used to regulate fan speed via three voltage levels. This enabled precise control of fan blade rotation. Raspberry Pi was employed as the edge computing platform for integrating software, data communication, and control logic.

Environmental conditions, such as temperature, humidity, airflow, and occupancy, were monitored using various sensors, including PIR-231-E modules. These devices detect temperature, motion, and wind speed to provide a comprehensive profile of the indoor space.

The Arduino system used the Arduino JSON library to encode transmitted control data in JSON format. Incoming string data were parsed and validated before being converted to structured control commands. Once the system was switched to auto mode, it stored these control parameters for real-time execution. The fan's speed was managed in three stages, while the IR heater and UV lamps were toggled using high/low signal relays. The system also stored a backup copy of the control state, allowing automatic restoration after manual override, and supported diagnostic output during maintenance operations.

Table 2. IoT devices used in this study.

Official Arduino UNO R3. [14].	Raspberry Pi 4 Model B. [15].	PIR-231-E Module from ICP DAS CO., LTD

3. Field survey

The experimental bathroom chamber was equipped with a wall-mounted control box, as shown in Figure 6, which included a manual override valve to allow the researchers to inspect and operate the system directly. UV lamps were installed on both sides of the exhaust fan. When the UV lights were activated, the fan was triggered simultaneously to generate airflow turbulence, helping airborne bacteria and fungi pass through the sterilisation field for effective disinfection.

An infrared (IR) heating lamp was also integrated into the system to raise the ambient temperature, reducing condensation and allowing moisture to be quickly expelled by the fan. This shortened the overall drying time. The IoT-based control architecture consisted of an automated web interface and a local manual control panel for flexible operation, as shown in Figure 7.

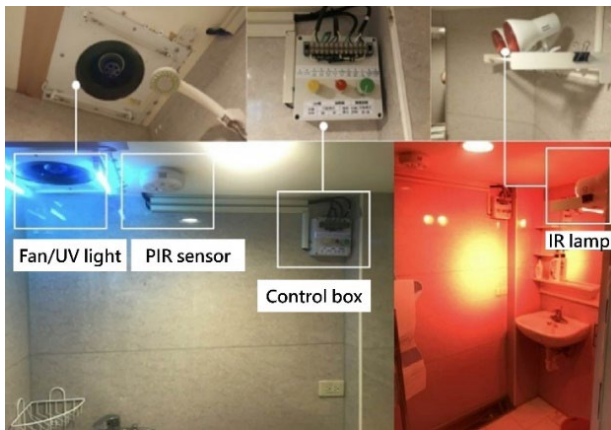


Figure 6. Equipment installation location diagram.

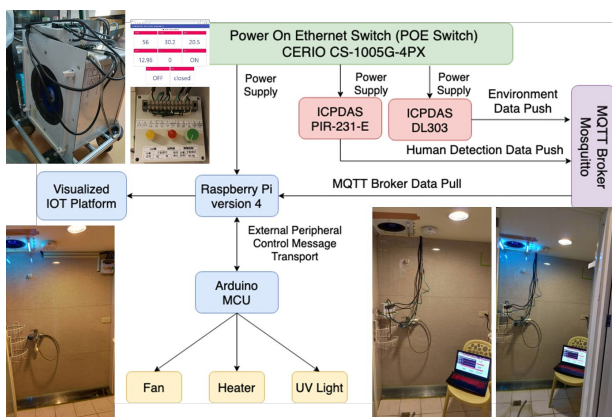


Figure 7. Fan control wiring diagram.

The experimental setup involved installing a control unit on the bathroom wall, as shown in Figure 6, equipped with a manual override switch to facilitate testing and adjustments by the researchers. UV lamps were mounted on both sides of the exhaust fan. When activated, the fan

induced airflow turbulence, allowing airborne bacteria and fungi to pass through the UV sterilisation field. Infrared (IR) heating lamps were used to raise the ambient temperature, preventing condensation and enabling rapid moisture removal via forced ventilation. This helped reduce the time needed to eliminate humidity from the space.

The entire system was governed by an IoT-based control architecture, which included both automated network-based controls and a local manual interface, as shown in Figure 7.

The system uploads control and environmental data to a web interface, allowing users and maintenance staff to monitor fan operations and system behaviour. Before each upload, it compares the current control state with the previous one, and data are sent to the Arduino only when a change is detected. This avoids redundant transmission and improves efficiency.

The web platform is built using Node.js and React. Upon startup, the Raspberry Pi automatically registers its IP and MAC address. The control system attempts to connect to the server and register the PIR-231 sensor. Once the system begins transmitting environmental data and control states, they are displayed in real time on the interface, allowing users to easily track current bathroom conditions and equipment status.

The system was installed in a test chamber where functionality and calibration were validated. A 6-hour monitoring session was conducted to capture temperature and humidity variations across different points, alongside a 24-hour test to assess bacterial and fungal concentrations. These tests were carried out under specific environmental control conditions as listed in Table 3.

Table 3. Sanitation and dehumidification control conditions in bathroom environments.

Humidity control	Temperature control	Sterilisation control
When the AH is higher than $0.021 \text{ kg/kg}'$, the fan will be turned on.	When the temperature is less than 29°C , the IR light will be turned on.	The UV lamp works with the fan at half speed for 10 min/h .
When the AH is lower than $0.015 \text{ kg/kg}'$, the fan will be turned off.	When the temperature is higher than 32°C , the IR light will be turned off.	When a person is detected by the system, the UV lamp will be shut down.

To evaluate system performance, a progressive intervention strategy was used, dividing the tests into two groups: Group A for dehumidification and Group B for sterilisation. The experimental procedures are outlined in Table 4.

Table 4. Experimental items and procedure.

Experimental Items	Experimental procedure
Experimental A-1	The fan is started with forced inlet air into the bathroom (air volume $110.1\text{ m}^3/\text{h}$, wind speed 0.79 m/s) until the end of the experiment.
Experimental A-2	The fan is started with forced inlet air into the bathroom (air volume $110.1\text{ m}^3/\text{h}$, wind speed 0.79 m/s) until the controlled fan shuts down.
Experimental A-3	It is the comparison item of Experiment A-1. The fan is started with IR lamps and forced inlet air into the bathroom (air volume $110.1\text{ m}^3/\text{h}$, wind speed 0.79 m/s) until the end of the experiment.
Experimental B-1	No fans running, UV lights, and forced inlet air. A substance is poured on the floor for 24 hours to culture bacteria.
Experimental B-2	After culturing bacteria, the control UV lamp with the fan at half speed is started for 10 min/h to monitor the colony-forming units for 24 hours.

The temperature before the experiment was about $26\text{--}28^\circ\text{C}$, the temperature of the shower water was 40 degrees, and the water flow rate was 10 l/min . After a 10-minute continuous shower simulation, the water was turned off. All experiments were conducted in the same test chamber and used consistent sensor locations. To reduce condensation, an infrared (IR) lamp was activated to raise the ambient temperature, and fresh air was forced in through the door gap. Based on Equation (1), the optimal ventilation rate was calculated as $110.1\text{ m}^3/\text{h}$ with an inlet opening area of 0.036 m^2 . This combination of increased temperature and controlled ventilation helped speed up the moisture removal process.

Additionally, a UV sterilisation system was installed. The UV lamp operated simultaneously with a fan running at half speed to create airflow turbulence, ensuring that airborne bacteria and fungi passed through the sterilisation zone. Since this experimental setup does not reflect the typical usage frequency of a residential bathroom, fungal growth was initially low. To simulate a more contaminated environment, an organic solvent was poured onto the floor and incubated for 24 hours to increase the microbial concentration for comparative analysis. The full test procedure is illustrated in Figure 8.



Figure 8. Shower experiment process.

4. Discussion

Data from both dehumidification (Experiment A) and sterilisation (Experiment B) were plotted and analysed to observe environmental trends. Measurements were taken at three indoor points (I1–I3) and one outdoor reference point (Outside, shown as Figure 4). Experiments included a 6-hour dehumidification phase and a 24-hour sterilisation phase, under ambient conditions of approximately $29\text{--}31^\circ\text{C}$ and $59\text{--}67\%$ relative humidity.

Each test began with a 10-minute hot water shower to simulate typical usage. The resulting warm, moist air rose due to thermal gradients and accumulated near the ceiling. When the sensors detected that the absolute humidity (AH) exceeded $0.021\text{ kg/kg}'$, the system automatically activated the fan for dehumidification, which continued until the AH dropped to $0.015\text{ kg/kg}'$.

The main difference between Experiments A-1 and A-2 was the use of continuous forced air intake. In A-2, both the fan and forced intake were shut off after about 20 minutes. This caused greater thermal stratification, as seen in Figures 10a and 10b, and allowed the external conditions to more strongly influence the indoor environment. Even after the fan was turned off, the sensors continued to detect AH levels above $0.015\text{ kg/kg}'$ for most of the test, suggesting a continued risk of mould growth.

In contrast, A-1 maintained constant air circulation throughout the experiment. Even after the fan shut down, the humidity decreased in a stepwise pattern over time, indicating that the environment remained within a safe range for most of the test ($\text{AH} < 0.015\text{ kg/kg}'$, with relative humidity between 40% and 60%). These results show that continuous forced ventilation significantly improves the dehumidification efficiency and provides more stable microbial control compared to intermittent strategies.

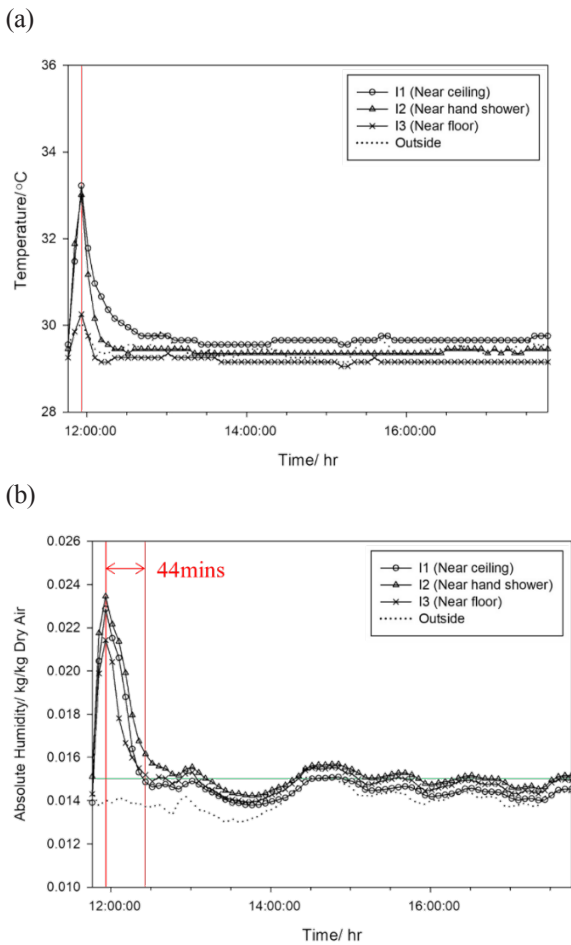


Figure 9. (a) A-1 Experimental temperature changes (continuous forced inlet air); and (b) A-1 Experimental absolute humidity changes (continuous forced inlet air).

In addition to using absolute humidity (AH) thresholds for system control, seasonal temperature variations must also be considered when determining the optimal environmental conditions. For example, maintaining the AH at or below 0.015 kg/kg is most effective when room temperatures fall to between 29°C and 36°C , an ideal range that supports 40–60% relative humidity and helps suppress fungal growth. When temperatures drop below 29°C , additional strategies such as prolonging fan operation or maintaining room temperature between 29°C and 32°C can help reduce moisture buildup. This not only lowers energy consumption but also prevents condensation from forming on surfaces after hot showers, minimising the risk of mould.

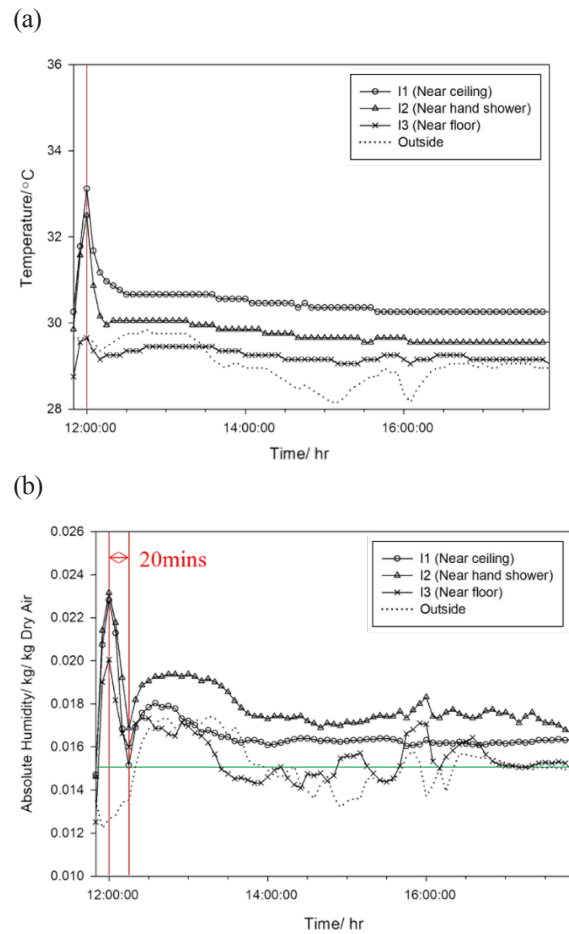


Figure 10. (a) A-2 Experimental temperature changes (without continuous forced inlet air); and (b) A-2 Experimental absolute humidity changes (without continuous forced inlet air)

Building on the results of Experiment A-1, Experiment A-3 introduced infrared (IR) heating in conjunction with fans and forced air intake. After approximately 18 minutes of operation, both the IR lamp and fan shut off automatically, while forced ventilation continued until the end of the test. As shown in Figure 11b, the inclusion of IR heating led to a smoother and more consistent decline in absolute humidity compared to A-1 (Figure 9b). Maintaining a stable temperature helped prevent condensation and allowed the fan to remove humidity more effectively. With an average ambient temperature of 31°C , the overall performance between A-1 and A-3 was similar. However, the IR lamp is expected to offer greater benefits under colder conditions.

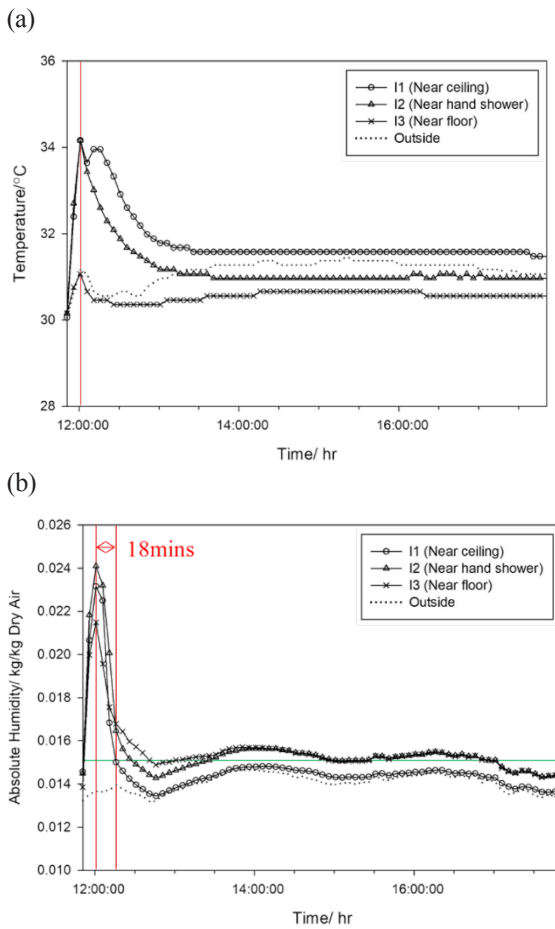


Figure 11. (a) A-3 Experiment with temperature changes (add IR light); and (b) A-3 Experimental absolute humidity changes (add IR light).

In the sterilisation experiment, organic matter was dropped onto the experimental bathroom floor ($1cm \times 1cm$) that had been previously wiped with alcohol, and after 24 hours, the colony-forming units of the floors were sampled and compared with those without UV light. Since the total colony-forming units were used as the sampling standard, there was less consideration of unknown species in the environment. The relative humidity changes during the cultivation and sterilisation processes are shown in Figure 12a. It can be observed that, under an average ambient temperature of $31^{\circ}C$, the relative humidity at all three points (I1-I3) in the space exceeded 60%, providing favourable conditions for fungal growth. The B-1 experiment conducted continuous measurements for 24 hours, with the results showing a floor-contact total bacterial concentration of $162\ cfu/m$, as shown in Figure 12b, and a fungal concentration in the air of $10\ cfu/m^3$. In the B-2 experiment, the UV lamp and exhaust fan (operating at half speed) were automatically activated for 10 minutes every hour, periodically disturbing the air in the bathroom. The results showed that the floor-contact total bacterial concentration was $0\ cfu/ml$, as shown in Figure 13b, and the

fungal concentration in the air was $0\ cfu/m^3$. Comparative results from the sterilisation experiment indicate that the operational strategy of using the UV lamp in combination with the fan effectively achieves sterilisation.

In the sterilisation experiment, changes in relative humidity were observed during both microbial cultivation and disinfection phases. Wang et al. (2020) demonstrated that infrared (IR) heating effectively raises the ambient temperature and prevents condensation, while UV-C lamps operating at $254\ nm$ are highly effective in deactivating fungal spores. Their findings support the design logic of the system and provide a theoretical foundation in this study.

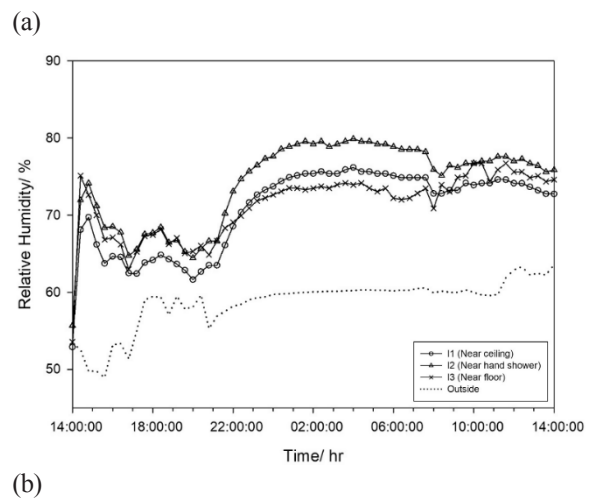


Figure 12. (a) B-1 Experimental relative humidity changes; and (b) B-1 Colony-forming units (CFUs) in $162\ cfu/ml$ (before the fan was integrated with the UV lamp).

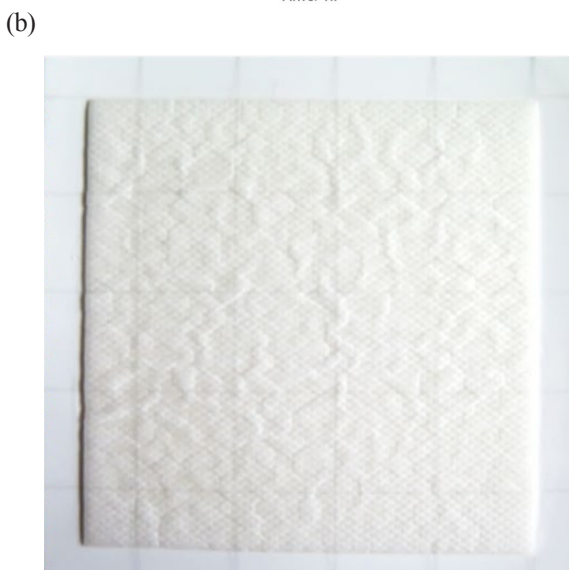
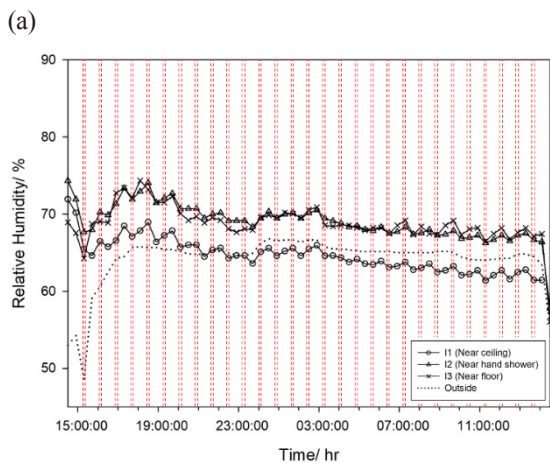


Figure 13. (a) B-2 Variation in Relative Humidity during the Experiment; and (b) B-2 Colony-forming units (CFUs) in 0 cfu/ml (after the fan was integrated with the UV lamp)

5. Conclusion

This study proposed a smart sterilisation and dehumidification ventilation system that integrates IoT sensors with real-time environmental control logic. Looking ahead, the system could be further integrated with existing bathroom infrastructure or combined with indoor air quality monitoring platforms, contributing to the broader goal of creating healthier and smarter residential environments.

Through the development of IoT-based control and field validation, the system addresses common issues of moisture accumulation and poor ventilation that often lead to mould growth in bathrooms. Using cloud-based analytics and preset control thresholds, the system continuously monitors temperature and humidity levels. It automatically activates fans when the absolute humidity exceeds $0.021 \text{ kg/kg}'$ and deactivates them when it falls below $0.015 \text{ kg/kg}'$. The IR heating lamp, fan, and UV

steriliser are also triggered when the ambient temperature drops below 29°C to maintain a balanced indoor climate. An IR lamp is used to heat and evaporate the liquid water on the surface of walls and the ground into gaseous water (water vapour), thereby accelerating dehumidification. The humidity control method is adapted to absolute humidity for evaluation to avoid the difference in relative humidity caused by changes in temperature, which would result in a less reasonable humidity control mechanism. The IR and UV lamps are turned off when a person is detected entering to avoid harm to the human body.

Field testing confirmed the effectiveness of the system design, but more tests will be conducted to average the results in later investigations. The results also highlighted the importance of combining ventilation fans, IR heating, and UV sterilisation with continuous forced air intake to ensure fast, stable, and effective dehumidification and microbial control.

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