International Journal on Advanced Science Engineering Information Technology

Vol.15 (2025) No. 1
ISSN: 2088-5334

Thermal Comfort Quality Monitoring and Controlling using Fuzzy Inference System Based on IoT Technology

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***Abstract*— The environment indoor quality (EIQ) is linked to human health, comfort, performance, and well-being. Thermal comfort quality (TCQ) is one of the most critical issues in the quality of the EIQ. Thermal comfort pollutants (TCP), consisting of temperature and humidity, significantly impact the quality of human life because indoor pollutants are ten times worse than outdoor air pollutants. This research presents TCP monitoring and controlling using a fuzzy inference system (FIS) based on IoT technology to detect, control, identify, and classify the thermal comfort index (TCI) in four levels: most comfort, not comfort, and least comfort. This research used the IoT concept to monitor temperature and humidity toxicity levels. The results from the calibration tests for the temperature and humidity sensors show that the maximum error remains below 5% and that the sensors demonstrated high accuracy, with any deviations from the expected values being minimal and within the acceptable range. Prototype experiment results show that the system performs exceptionally well, with a maximum error between the prototype and the simulation of only 0.4%. The system can produce TCI ranges for most comfort (2.25-3), comfort (1.5-2.25), not comfort (0.75-1.5), and least comfort (0.75), with varying output responses for each cluster. Mechanical ventilation, alert, and notification output are presented to get efficient and accurate action to mitigate the TCP and notify the user about the TCP condition.**

***Keywords*—Environment indoor quality; thermal comfort quality; fuzzy inference system ; internet of things.**

Manuscript received 7 Aug. 2024; revised 23 Oct. 2024; accepted 5 Nov. 2024. Date of publication 28 Feb. 2025.

I. INTRODUCTION

Nowadays, environmental indoor quality (EIQ) is a serious concern to humans worldwide. EIQ refers to the quality of a building's environment concerning the human health, comfort, productivity, and well-being of those who occupy space within it [1]. EIQ is the most important aspect to ensure the health and comfort level of human beings because 80 - 90% of people spend their activities in indoor environments such as houses, offices, and schools, which further makes poor indoor environment quality a serious health concern [2], [3]. EIQ consists of various kinds of pollutants such as air pollutants, thermal comfort pollutants, water pollutants, toxic pollutants, solid waste pollutants, lighting, and acoustic comforts [4], [5].

Ensuring thermal comfort is essential for human health, as it significantly improves indoor environment quality, directly impacting human life and daily activities. Thermal comfort has wide connotations, including physical and psychological aspects and ambient characteristics [6]. Two parameters can influence thermal comfort quality (TCQ): internal and external parameters. Internal parameters are human personal parameters, including human metabolic rate and clothing. External parameters are environmental parameters inside the room, including air temperature, relative humidity, and air movement/velocity, as shown in Figure 1 [7], [8]. The most important environmental variables regarding the TCQ are air temperature (Ta), and relative humidity (RH) [9]. Sweating, eye strain, dizziness, increased breathing rate, dry and irritated eyes, feelings of warmth, and changes in heart rate are common symptoms reported in response to sudden changes in temperature and humidity. [10], [11], warm and cold discomfort can affect human performance and motivation [12].

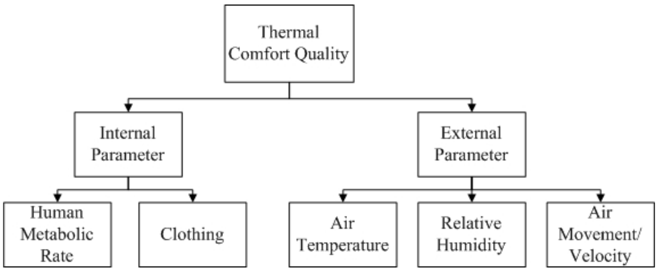

Fig. 1 TCQ Parameters

Several companies have created IoT-based TCQ monitoring technology to offer features such as sensor data readings, device-centric services, real-time data collection, data storage, interactive graphical interfaces, statistical analysis capabilities, and status notifications. Temperature and humidity real-time monitoring using FBG, SHT25, DHT11, and DHT22 provide good performance with minimal power consumption, high reliability, and long-term stability [13]–[15]. The Internet of Things (IoT) serves as the platform that interconnects sensors, software, and processors, enabling them to communicate with one another and with the user via an Android application [16]–[18]. The thermal comfort index (TCI) is a value that expresses satisfaction with the thermal comfort environment, and it is assessed by subjective evaluation of real-time temperature and humidity data collection. TCI can be defined as the temperature and humidity toxicity assessment guidance of the human health [19]–[21]. A FIS is employed to examine, arrange, and evaluate Indoor air pollutants based on logical operations (rules). This approach enhances the effectiveness of quality assessment and aligns precise concentration values within a fuzzy index [22]–[24]. Natural ventilation and mechanical ventilation are used to mitigate indoor air pollutants to get acceptable air quality using open-close windows, air purifiers, and humidifiers [25]–[27]. This work provides a good solution for monitoring, assessing, and controlling thermal comfort pollutants. Moreover, the main gap is that previous research used only the system separately, producing a less efficient and sensitive system.

In this research, the authors build a monitoring and controlling system to detect, assess, and mitigate the thermal comfort pollutants (TCP) consisting of temperature and humidity using a FIS on IoT technology. TCI is the main reference index containing temperature and humidity. A FIS employing logical reasoning will identify, categorize, evaluate, and offer guidance on the toxicity levels of temperature and humidity. Mechanical ventilation (fan DC) automatically increases the thermal comfort inside the room based on TCI conditions. Also, this system will send notifications and alerts to the Android application of the TCI conditions. The author's contribution lies in creating an effective and precise TCQ monitoring and control system by implementing a FIS system that integrates with control outputs, alert notifications, and display functions.

II. MATERIALS AND METHOD

The proposed system architecture scheme consists of four stages, shown in Figure 2. TCQ monitoring and controlling using a FIS based on IoT technology is taught to gather real-time temperature and humidity data and assess and identify the TCI status. The FIS determines TCQ by considering various temperature and humidity levels. This system operates through three processes: fuzzification, inference, and defuzzification. Fuzzification is the process of transforming precise inputs, such as temperature and humidity, into fuzzy values. These fuzzy values are then interpreted into membership degrees within a fuzzy set based on predefined membership functions. The outcome of fuzzification is fuzzy values that may belong to one or more fuzzy sets, with membership degrees indicated by values ranging from 0 to 1.

The inference system applies predefined fuzzy rules to manage the fuzzy input values. These fuzzy rules follow an IF-THEN structure, linking input conditions to possible outputs. This process combines the rule outcomes using fuzzy operators like AND (min) and OR (max). The implication function dictates how the fuzzy output is affected by the membership degrees of the fuzzy inputs. Defuzzification converts the fuzzy output produced by the inference system back into crisp values that can be used as outputs for control systems. The defuzzification process results in a distinct numerical value that reflects the system's action or response based on the original input conditions [28]–[30].

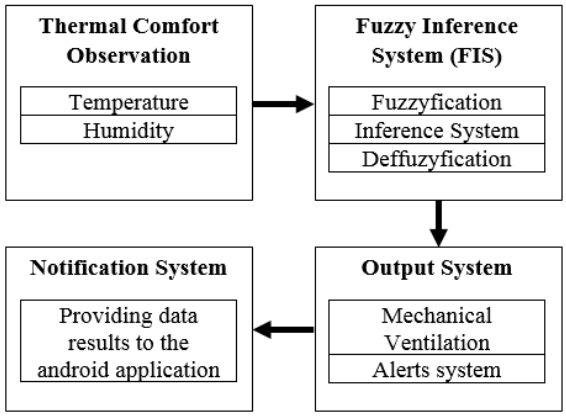

Fig. 2 Architecture of Thermal Comfort Quality (TCQ) System

A. *Thermal comfort quality (TCQ) design*

The TCQ monitoring and controlling using various hardware connected to one system is shown in Figure 3. The DHT22 sensor detects and gathers temperature and humidity data in this system. It features a thermistor for measuring dry bulb temperature and a humidity sensor that gauges moisture levels by detecting changes in the conductivity of a moisture-sensitive substrate material [31]. ESP8266 is used to interface the microcontroller, and it uploads the TCQ data to the IoT platforms through Wi-Fi using the API key (Application program interface)[32]. IoT platforms make the TCQ visible to the users. The LCD shows the temperature, humidity, and TCI of the human inside the room. The control system consists of mechanical ventilation (inlet-outlet exhaust) and alert output (LED and buzzer), which notify humans and mitigate TCP inside the room. Arduino UNO connects the sensor, output, and notify system into one system. It includes 14 digital input/output pins (six of which can be used as PWM outputs), 6 analog input pins, 32 KB of Flash memory, and 1 KB of EEPROM [33]. Arduino UNO is also used to calculate and assess the FIS process of temperature and humidity variables in the TCI variable. The hardware is placed inside a box within a room to monitor the temperature, humidity, and

TCI) within the room. This device is a prototype scaled at 1:4 for a room size of 8m x 4m x 4m.

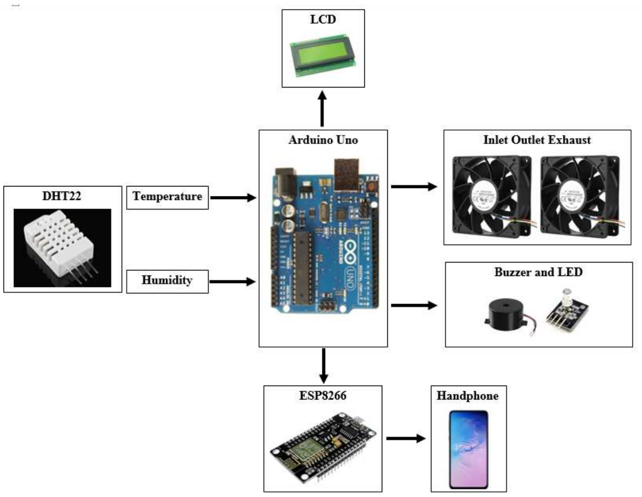

Fig. 3 Block diagram of thermal comfort quality monitoring and controlling system

The TCI and temperature and humidity data sensor information are also calculated for an indoor place. The TCI describes the TCQ of the air at a given location. Computing the TCI requires a TCP toxicity level from a monitor or mode. TCI values are categorized into various ranges, each assigned a specific descriptor and color code. This signifies that each range corresponds to different effects on human health. [34]. Dionova breaks the TCI into four levels of health concerns [22] as described in Table 1. The purpose of TCI is to help users understand the toxicity level of temperature and humidity on human health.

TABLE I
THERMAL COMFORT POLLUTANTS THRESHOLD POINT

Temp (^0c)	Humidity (%)	TCI	TCI status	Remarks
18-25	40-70	2.25-3	Most Comfort	Poses minimal or no risk
22-29	60-80	1.5-2.25	Comfort	Within acceptable range, but could pose a moderate health concern for sensitive individuals
26-39	70-90	0.75-1.5	Not Comfort	Sensitive groups might experience health effects
32-45	80-100	0-0.75	Least Comfort	Everyone might face significant health impacts

Figure 4 shows the TCQ workflow using a FIS. The microcontroller collects the temperature and humidity data from the DHT22 sensor. After obtaining the temperature and humidity concentration, the TCI FIS box is divided into three steps: fuzzifying each input variable, selecting the rule base, and defuzzification. Fuzzification converts clear, numerical data (crisp values) from thermal comfort quality parameters (temperature and humidity) into fuzzy values. This process helps categorize the data into fuzzy sets such as “most comfort,” “comfort,” “not comfort,” or "least comfort” based on membership degrees. In other words, fuzzification allows continuous thermal comfort data to be linguistically understood and analysed, facilitating the evaluation and decision-making regarding TCQ in indoor environments. This process is the initial step in a fuzzy logic system, aiding in determining the quality category and providing a more intuitive understanding of indoor environmental conditions.

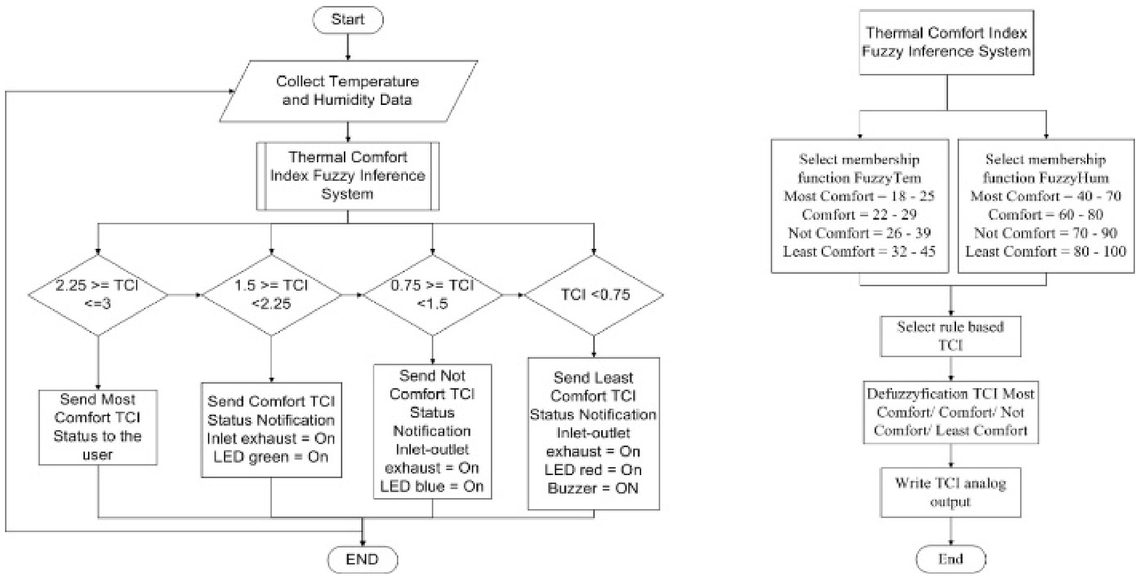

Fig. 4 Flow work of thermal comfort quality monitoring and controlling using FIS.

Rule base defines the logical rules that connect various parameters of TCP) with the overall TCQ assessment. The rule base serves as a framework to determine how different combinations of parameter values (temperature and humidity) lead to decisions about the overall TCI. It involves establishing IF-THEN rules that define the relationship between temperature and humidity values and the cluster index value and considering parameter combinations to provide a more accurate and comprehensive value. Defuzzification converts the fuzzy output produced by the fuzzy logic inference system into a clear numerical value (TCI) that can be used for further decision-making or actions.

Defuzzification results in a precise numerical value, such as a TCQ index (e.g., 0-3), where higher numbers indicate better TCI. This TCI FIS will convert the temperature and humidity into the TCI in four stages: most comfort, comfort, not comfort, and least comfort. Four conditions based on the TCI value conditions have different notifiers to the user and output control response.

B. Thermal comfort index (TCI) of fuzzy Inference System (FIS)

A FIS incorporates the expertise and knowledge of a specialist in designing systems to manage processes where fuzzy control rules govern input-output relationships. The Sugeno-type method (also known as Takagi-Sugeno-Kang) features fuzzy inputs and produces a crisp output through a linear combination of the inputs. This method is computationally efficient and well-suited for optimization and adaptive techniques, making it highly effective for control problems [35]. Three main parts convert temperature and humidity into TCI: fuzzification, inference system, and defuzzification.

The first of the FIS steps is fuzzification, which classifies crisp input into linguistic variables. Concentration levels of temperature and humidity act as precise inputs and are transformed into linguistic values using corresponding membership functions (MFs). Each membership function is defined by the X-axis, representing the range of possible values, and the Y-axis, indicating the degree of membership from 0 to 1.[36]. The approach used in this research for the input fuzzification was the triangular and trapezoidal methods. The triangle membership function was used to compare three transformation states of temperature and humidity values, which show sharp variations. Its main benefit is its ability to detect minor temperature-humidity changes and facilitate accurate and fast decision-making for the control process. On the other hand, trapezoidal membership functions effectively manage uncertainty and imprecision by offering a broader range of values with full membership. This is especially beneficial in cases where exact precision temperature and humidity are not essential, and a range of acceptable values can be used.

Four linguistic variables of temperature, most comfort, comfort, not comfort, and least comfort, are used, as shown in Figure 5. The X-axis represents the change rate value of temperature from 20 to 45^{0}C, and the y-axis represents the degree of membership from 0 to 1. Most comfort linguistic variables range from 18 to 25^{0}C; comfort ranges from 22 to 29^{0}C; not comfort ranges from 26 to 39^{0}C; and the least comfort ranges from 32 to 45^{0}C.

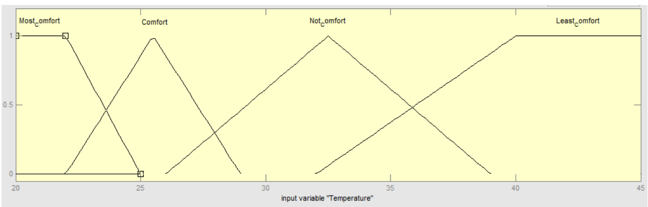

Fig. 5 Input temperature FIS membership function

Four linguistic variables of humidity, most comfort, not comfort, and least comfort, are used, as shown in Figure 6. The X-axis represents the change rate value of humidity from 40 to 100%, and the y-axis represents the degree of membership from 0 to 1. Most comfort linguistic variables range from 40 to 70%; comfort ranges from 60 to 80%; not comfort ranges from 70 to 90%; and the least comfort ranges from 80 to 100%.

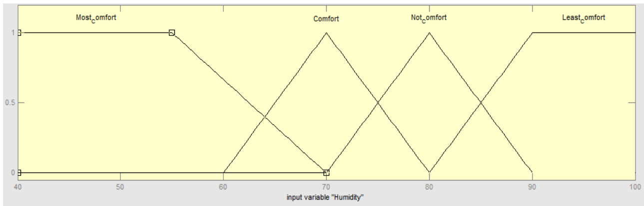

Fig. 6 Input humidity FIS membership function

The second step involves the inference system, which establishes the input-output relationship by translating linguistic variables into fuzzy output values. Inference rules are created based on combinations of thermal comfort quality parameters. These rules are designed to assess the potential harm of concentration and determine the appropriate thermal comfort condition. The interface engine receives the linguistic variables of each input and compares the input data with the IF-THEN statements [37]. Table 2 presents the sixteen rules for two inputs, each categorized into four levels. The rules indicate that the provided input determines the corresponding TCI level.

TABLE II
TCI RULE BASE INFERENCE SYSTEM

		Humidity Index			
Temperature Index	Thermal Level Index	Most Comfort	Comfort	Not Comfort	Least Comfort
	Most Comfort	Most Comfort	Comfort	Comfort	Comfort
	Comfort	Comfort	Comfort	Not Comfort	Not Comfort
	Not Comfort	Comfort	Not Comfort	Not Comfort	Not Comfort
	Least Comfort	Comfort	Not Comfort	Not Comfort	Least Comfort

The inference system produces a fuzzy output based on the input from the fuzzy rule base. This output must be converted into a clear value to be interpretable. The third step, defuzzification, transforms the fuzzy output into a non-fuzzy (crisp) value. In the Sugeno-type FIS, the non-fuzzy output value is calculated using a weighted average. The membership functions used are constant. According to Table 2, four categories—Most Comfort, Comfort, Not Comfort, and Least Comfort—are used to define the membership functions for the output variable TCI, as illustrated in Figure 7.

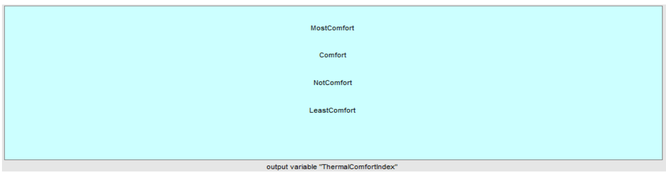

Fig. 7 FIS membership function of TCI as the output variable

III. RESULTS AND DISCUSSION

The main purpose of the system is to detect and keep the TCI at a safe level of temperature and humidity standard [22]. The inlet-outlet exhaust, LED, and buzzer operate according to the TCI condition. A simulation was conducted to evaluate the performance of the TCQ system. This test aimed to assess how effectively the system monitors and evaluates temperature and humidity across various toxicity levels. The test was carried out with four scenarios: The first scenario when the TCI condition at the most comfort status; The second condition when the TCI condition at the comfort status; The third condition when the TCI condition at the not comfort status; The fourth condition when the TCI condition at the least comfort status. So, the simulation and practical results can be compared to determine the system's performance based on the simulation's design.

The simulation result of the TCI rule viewer is shown in Figure 8. The first column in the rule viewer shows the rate of change in temperature concentration, while the second column displays the rate of change in humidity concentration; together, these columns represent the input values. The third column provides the output, which indicates the TCI the level of thermal comfort pollutants). With a temperature concentration of 23.6°C and a humidity concentration of 74%, the TCI output is 1.77, indicating a "Comfort" level.

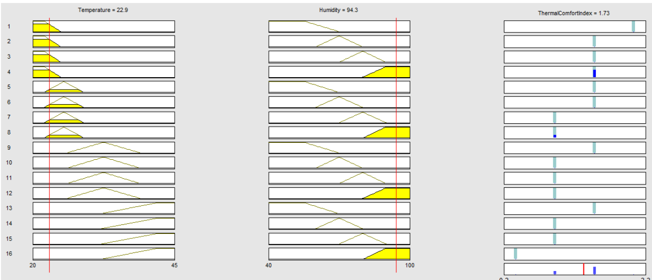

Fig. 8 TCI FIS output

Figure 9 illustrates these TCI results graphically using a surface viewer. The X-axis displays the temperature input values, the Y-axis represents the humidity input values, and the Z-axis indicates the output value of cluster index 4 (which ranges from 0 to 3).The graph features four color dimensions: yellow for "Most Comfort," green for "Comfort," light blue for "Not Comfort," and dark blue for "Least Comfort." This indicates that the TCI is affected by both temperature and humidity concentrations. The plot reveals that as the level of each thermal comfort pollutant increases, the TCI value drops sharply, regardless of the other pollutant's value.

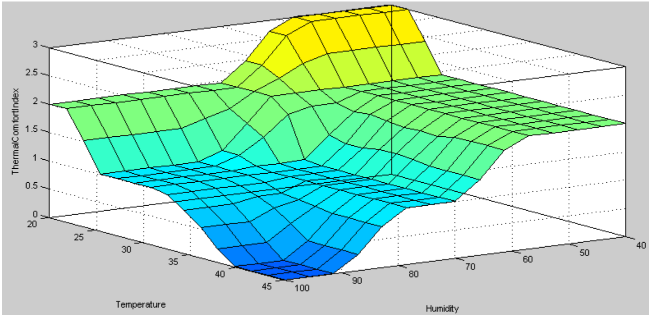

Fig. 9 TCI MATLAB surface viewer

Data collection is manually done every minute from 08:41 to 16:41 for the temperature and humidity sensor (DHT22). This DHT22 sensor can detect temperature concentrations from -40 to 80 0C and humidity concentrations from 0 to 100 %. Data is collected in a room that has an air conditioner (AC) as an input source that can reduce the value of temperature concentration and increase the value of humidity concentration and hot water as an input source that can increase the value of temperature concentration and reduce the value of humidity concentration. The sensor calibration results show good performance, with the sensor readings having an error percentage below 5%. However, the sensor readings still do not categorize status levels effectively, as some values fall within two distinct levels.

TABLE III
TEMPERATURE AND HUMIDITY (DHT22) DATA RETRIEVAL

Time	Temperature sensor (^{0}C)	Temperature Thermometer (^{0}C)	Temperature % error	Temperature status	Humidity sensor%	Humidity thermometer	Humidity error	Humidity status
08:41	25.2	24.4	3.28	Most comfort/ comfort	68	65	4.62	Most comfort/ comfort
10:52	21.7	22.8	4.82	Most comfort/ comfort	60	58	3.45	Most comfort
11:25	25.1	24.3	3.29	Comfort	74.4	72	3.33	Comfort
13:17	26.6	25.8	3.10	Comfort/ not comfort	83.9	82	2.32	Not comfort/ least comfort
16:40	32.1	31.3	3.07	Not comfort	92.1	90	2.33	Least comfort

DHT22 was used to obtain concentration of temperature and humidity values. DHT22 uses a digital input port to recite the temperature and humidity from a sensor. To get the temperature value in units (^{0}C) and humidity in unis (%), the program used is $temperature = dht.readTemperature()$ and $humidity = dht.readHumidity()$. The DHT22 sensor employs a capacitor and thermistor to measure the surrounding air and transmit signals through the data pin. DHT22 is noted for its high reading quality, characterized by its rapid data acquisition response and compact size. The LCD will provide temperature, humidity, TCI score, and TCI status shown in Figure 10 (A) most comfort status (LED off), (B) comfort status (LED green), (C), not comfort (LED blue), and (D) least comfort (LED red).

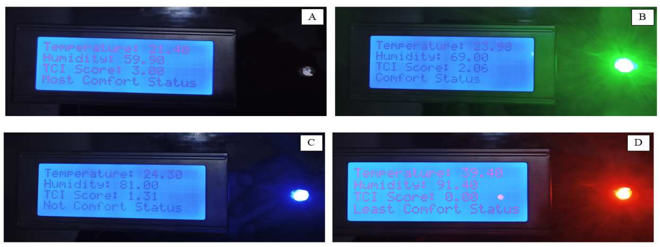

Fig. 10 Implementation of thermal comfort quality (TCQ) system (A) Most comfort status, (B) Comfort status, (C) Not comfort status, and (D) Least comfort status

The microcontroller works to read two thermal comfort pollutants concentrations, the index value calculation using the FIS, and will be stored in a Thing Speak database, also displayed via the mobile application display. Data recorded and saved by the microcontroller and Wi-Fi module is connected to the internet network. The data displayed in the mobile application is the sensor reading data, calculating the index value every five seconds because the sensors need time to stabilize the reading process. The notification will be running automatically based on the system reading process. Figure 11 shows that the system can classify the temperature and humidity into four specific levels (A) most comfort, (B) comfort, (C) not comfort, and (D) least comfort. Output from ThingSpeak cloud: Figure. 12 illustrates the line chart output from ThingSpeak cloud. Figure. 13 illustrates the notification output from the ThingSpeak cloud.

Fig. 11 Android application of thermal comfort quality (TCQ) system (A) Most comfort status, (B) Comfort statuts, (C) Not comfort status, and (D) Least comfort status

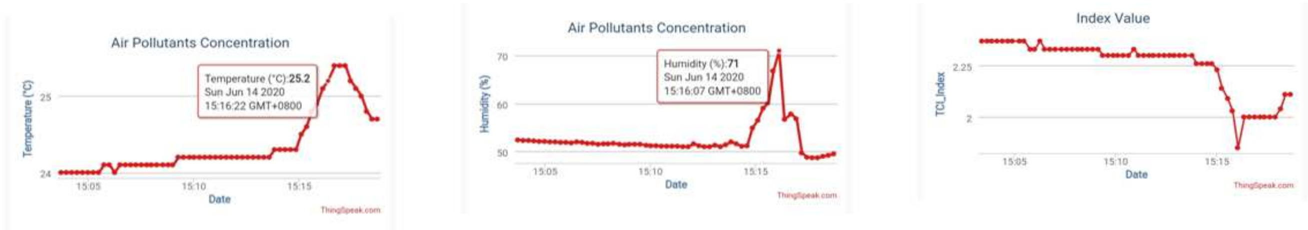

Fig. 12 Android application of thermal comfort quality (TCQ) system charts

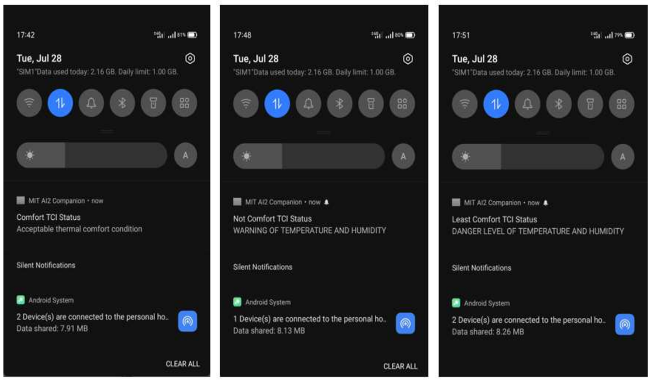

Fig. 13 Android application of thermal comfort quality (TCQ) system notifications

Ten different temperature and humidity values were tested to assess the accuracy of input-output outcomes and the effectiveness of the fuzzy model in detecting the TCI and its corresponding category, as shown in Table 4. The actual output is derived from MATLAB simulations, while the expected output is obtained by manually comparing the TCI categories of temperature and humidity. The comparison between the practical and theory values is very small, with a percentage error value below 0.4%. It can be interpreted that the prototype made had the same performance as the proposed simulation. Fuzzy logic with the Sugeno method provides excellent precision in calculating the output index values based on two pollutant inputs with several different status levels.

TABLE IV
TCI MONITORING RESULTS

No	Temperature (^{0}C)	Humidity (%)	TCI Value (Practical)	TCI Value (Simulation)	TCI % error	TCI status
1	21.4	59.9	3	3	0	Most comfort
2	22.3	68	2.1207	2.12	0.03302	Comfort
3	22.6	83.4	1.7447	1.74	0.27011	Comfort
4	22.9	94.3	1.7313	1.73	0.07514	Comfort
5	23.9	69	2.0639	2.06	0.18932	Comfort
6	24.3	81	1.3057	1.31	0.32824	Not comfort
7	25.2	93.3	1	1	0	Not comfort
8	33.2	86.5	0.9032	0.903	0.02215	Not comfort
9	33.6	92	0.8385	0.839	0.05959	Not comfort
10	39.4	91.4	0	0	0	Least comfort

IV. CONCLUSION

A new generation of IoT is presented, aiming to monitor and control the physical air quantities affecting thermal comfort quality. Monitoring accumulated data in cloud storage helps analyze various patterns in environmental parameters and accordingly notifies the public. Several experimental results confirm that the performance of the chosen sensor nodes is quite good for the intended application. The results also illustrate the ability of fuzzy sets to integrate diverse knowledge and translate it into clearer indices for environmental management. The Takagi-Sugeno-type inference method was employed due to its effectiveness in data processing and suitability for optimization issues. This FIS accurately finds the TCI and is thus capable of monitoring real-time pollution. Its dynamic nature allows it to adapt to varying conditions and TCI levels across different geographical locations.

REFERENCES

[1] S. Kaveh, A. Habibi, M. Nikkar, and A. Aflaki, "Nature-based solutions optimizing green infrastructure strategies for microclimate regulation and air quality improvement in urban environments: A case study," *Nat.-Based Solut.*, vol. 6, p. 100167, Jun. 2024, doi:10.1016/j.nbsj.2024.100167.

[2] A. Ackley et al., "Indoor environmental quality (IEQ) in healthcare facilities: A systematic literature review and gap analysis," *J. Build. Eng.*, vol. 86, Jan. 2024, doi: 10.1016/j.jobe.2024.108787.

[3] M. I. S. Veríssimo, "A critical review of the analytical performance of the most recent MOS-based gas sensors for indoor air quality monitoring of WHO priority pollutants," *TrAC, Trends Anal. Chem.*, vol. 178, p. 117813, Apr. 2024, doi: 10.1016/j.trac.2024.117813.

[4] P. Wargocki et al., "TAIL, a new scheme for rating indoor environmental quality in offices and hotels undergoing deep energy renovation (EU ALDREN project)," *Energy Build.*, vol. 244, pp. 1–13, 2021, doi:10.1016/j.enbuild.2021.111029.

[5] S. Nehr, L. Baus, H. Çınar, I. Elsen, and T. Frauenrath, "Indoor environmental quality assessment in passively ventilated classrooms in Germany and estimation of ventilation energy losses," *J. Build. Eng.*, vol. 97, p. 110937, Jul. 2024, doi: 10.1016/j.jobe.2024.110937.

[6] T. Al Mindeel, E. Spentzou, and M. Eftekhari, "Energy, thermal comfort, and indoor air quality: Multi-objective optimization review," *Renew. Sustain. Energy Rev.*, vol. 202, p. 114682, Sep. 2024, doi: 10.1016/j.rser.2024.114682.

[7] A. J. Werner-Juszczuk and A. Siuta-Olcha, "Assessment of the impact of setting the heating curve on reducing gas consumption in a residential building while ensuring thermal comfort," *J. Build. Eng.*, vol. 94, p. 110032, Jun. 2024, doi: 10.1016/j.jobe.2024.110032.

[8] P. Wolkoff, K. Azuma, and P. Carrer, "Health, work performance, and risk of infection in office-like environments: The role of indoor temperature, air humidity, and ventilation," *Int. J. Hyg. Environ. Health*, vol. 233, p. 113709, Sep. 2021, doi:10.1016/j.ijheh.2021.113709.

[9] M. Hou et al., "Resolving indoor shortwave and longwave human body irradiance variations for mean radiant temperature and local thermal comfort," *Energy Build.*, vol. 301, p. 113581, Sep. 2023, doi:10.1016/j.enbuild.2023.113581.

[10] D. H. Phan, "Adverse effects of extreme temperature on human development: Empirical evidence from household data for Vietnam across regions," *Ecol. Econ.*, vol. 225, p. 108343, Jul. 2024, doi:10.1016/j.ecolecon.2024.108343.

[11] R. Afroz et al., "Assessments and application of low-cost sensors to study indoor air quality in layer facilities," *Environ. Technol. Innov.*, vol. 36, p. 103773, Jun. 2024, doi: 10.1016/j.eti.2024.103773.

[12] W. Cui, G. Cao, J. H. Park, Q. Ouyang, and Y. Zhu, "Influence of indoor air temperature on human thermal comfort, motivation and performance," *Build. Environ.*, vol. 68, pp. 114–122, 2013, doi:10.1016/j.buildenv.2013.06.012.

[13] M. K. Mathew, R. G. J. Valooran, and N. K. Vaegae, "An effective temperature monitoring scheme using ANN-based fiber Bragg grating sensor," *Int. J. Intell. Eng. Syst.*, vol. 10, no. 4, pp. 109–116, 2017, doi:10.22266/ijies2017.0831.12.

[14] M. N. A. Ramadan, M. A. H. Ali, S. Y. Khoo, M. Alkhedher, and M. Alherbawi, "Real-time IoT-powered AI system for monitoring and forecasting of air pollution in industrial environment," *Ecotoxicol. Environ. Saf.*, vol. 283, p. 116856, Apr. 2024, doi:10.1016/j.ecoenv.2024.116856.

[15] A. Beniwal, P. Ganguly, A. K. Aliyana, G. Khandelwal, and R. Dahiya, "Screen-printed graphene-carbon ink based disposable humidity sensor with wireless communication," *Sens. Actuators B, Chem.*, vol. 374, p. 132731, Jul. 2023, doi:10.1016/j.snb.2022.132731.

[16] H. Xi, B. Wang, and W. Hou, "Machine learning-based prediction of indoor thermal comfort in traditional Chinese dwellings: A case study of Hankou Lifen," *Case Stud. Therm. Eng.*, vol. 61, p. 105048, Apr. 2024, doi: 10.1016/j.csite.2024.105048.

[17] J. Xin, X. Shi, F. Ye, C. Zhenlei, P. Yin, and B. Miao, "Evaluation of the air quality and the thermal comfort in the kitchen fume environment under the fresh air supplement," *Results Eng.*, vol. 23, p. 102681, Jan. 2024, doi: 10.1016/j.rineng.2024.102681.

[18] R. Elise, V. Der Walt, S. Susanna, and M. Johannes, "Dataset of indoor air parameter measurements relating to indoor air quality and thermal comfort in South African primary school classrooms of various building infrastructure types," *Data Brief*, vol. 53, p. 110045, 2024, doi: 10.1016/j.dib.2024.110045.

[19] S. Miao, M. Gangolells, and B. Tejedor, "Data-driven model for predicting indoor air quality and thermal comfort levels in naturally ventilated educational buildings using easily accessible data for schools," *J. Build. Eng.*, vol. 80, p. 108001, Jul. 2023, doi:10.1016/j.jobe.2023.108001.

[20] S. Ghani, A. Osama, F. Bakochristou, and E. A. Elbialy, "Assessment of thermal comfort indices in an open air-conditioned stadium in hot and arid environment," *J. Build. Eng.*, vol. 40, p. 102378, 2021, doi:10.1016/j.jobe.2021.102378.

[21] M. Badasa and D. Obsi, "Assessment of urban thermal field variance index and thermal comfort level of Addis Ababa metropolitan city, Ethiopia," *Heliyon*, vol. 8, no. 8, p. e10185, 2022, doi:10.1016/j.heliyon.2022.e10185.

[22] B. W. Dionova, M. N. Mohammed, S. Al-Zubaidi, and E. Yusuf, "Environment indoor air quality assessment using fuzzy inference system," *ICT Express*, 2020, doi: 10.1016/j.icte.2020.05.007.

[23] H. Hamidane, S. E. L. Faiz, I. Rkik, M. El Khayat, A. Ed-dahhak, and A. Lachhab, "Constrained temperature and relative humidity predictive control: Agricultural greenhouse case of study," *Inf. Process. Agric.*, vol. 11, no. 3, pp. 409–420, 2024, doi:10.1016/j.inpa.2023.04.003.

[24] Q. W. Khan, R. Ahmad, A. Rizwan, A. N. Khan, K. T. Lee, and D. H. Kim, "Optimizing energy efficiency and comfort in smart homes through predictive optimization: A case study with indoor environmental parameter consideration," *Energy Rep.*, vol. 11, pp. 5619–5637, Oct. 2024, doi: 10.1016/j.egyr.2024.05.038.

[25] F. López Plazas and C. Sáenz de Tejada, "Natural ventilation to improve indoor air quality (IAQ) in existing homes: The development of health-based and context-specific user guidelines," *Energy Build.*, vol. 314, Apr. 2024, doi: 10.1016/j.enbuild.2024.114248.

[26] S. Oh et al., "Effects of air purifiers and ventilation on particulate matter concentration at semi-outdoor space," *J. Clean. Prod.*, vol. 434, p. 139903, Jul. 2024, doi: 10.1016/j.jclepro.2023.139903.

[27] T. Kumar and A. Doss, "AIRO: Development of an intelligent IoT-based air quality monitoring solution for urban areas," *Procedia Comput. Sci.*, vol. 218, pp. 262–273, 2022, doi:10.1016/j.procs.2023.01.008.

[28] C. Napole, O. Barambones, M. Derbeli, and I. Calvo, "Design and experimental validation of a piezoelectric actuator tracking control based on fuzzy logic and neural compensation," *Fuzzy Sets Syst.*, vol. 464, p. 108449, 2023, doi: 10.1016/j.fss.2022.12.005.

[29] S. Loganathan, D. Ramakrishnan, M. Sathiyamoorthy, and H. M. Azamathulla, "Assessment of irrigational suitability of groundwater in Thanjavur district, Southern India using Mamdani fuzzy inference system," *Results Eng.*, vol. 21, p. 101789, Jan. 2024, doi:10.1016/j.rineng.2024.101789.

[30] K. Pujaru, S. Adak, T. K. Kar, S. Patra, and S. Jana, "A Mamdani fuzzy inference system with trapezoidal membership functions for investigating fishery production," *Decis. Anal. J.*, vol. 11, p. 100481, Jun. 2024, doi: 10.1016/j.dajour.2024.100481.

[31] F. Irwanto et al., "IoT and fuzzy logic integration for improved substrate environment management in mushroom cultivation," *Smart Agric. Technol.*, vol. 7, p. 100427, Mar. 2024, doi:10.1016/j.atech.2024.100427.

[32] Y. Ayat, A. El Moussati, and I. Mir, "Revolutionizing air quality monitoring: IoT-enabled e-noses and low-power devices," *IFAC-PapersOnLine*, vol. 58, no. 13, pp. 829–834, 2024, doi:10.1016/j.ifacol.2024.07.585.

[33] E. Collado et al., "Open-source Internet of Things (IoT)-based air pollution monitoring system with protective case for tropical environments," *HardwareX*, vol. 19, Jan. 2024, doi:10.1016/j.ohx.2024.e00560.

[34] M. M. Islam, F. A. Jibon, M. M. Tarek, M. H. Kanchan, and S. U. P. Shakil, "A real-time dataset of air quality index monitoring using IoT and machine learning in the perspective of Bangladesh," *Data Brief*, vol. 55, p. 110578, 2024, doi: 10.1016/j.dib.2024.110578.

[35] H. Sarkheil, S. Rahbari, and Y. Azimi, "Fuzzy-Mamdani environmental quality assessment of gas refinery chemical wastewater in the Pars special economic and energy zone," *Environ. Challenges*, vol. 3, p. 100065, Jan. 2021, doi: 10.1016/j.envc.2021.100065.

[36] S. Yordanova, B. Gueorguiev, and M. Slavov, "Design and industrial implementation of fuzzy logic control of level in soda production," *Eng. Sci. Technol., Int. J.*, vol. 23, no. 3, pp. 691–699, 2020, doi: 10.1016/j.jestch.2019.08.005.

[37] A. Aggarwal, T. Choudhary, and P. Kumar, "A fuzzy interface system for determining Air Quality Index," in *Proc. 2017 Int. Conf. Infocom Technol. Unmanned Syst. Trends Futur. Dir. (ICTUS)*, 2018, pp. 786–790, doi: 10.1109/ICTUS.2017.8286113.