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Smart classroom 4.0 using embedded systems for attendance, energy monitoring, and environmental control

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ABSTRACT

The increasing demand for digitalization and energy efficiency in vocational education has encouraged the development of intelligent classroom systems. This study proposes an integrated smart classroom 4.0 system based on the internet of things (IoT) and embedded systems to improve attendance management, electrical safety, energy efficiency, and environmental monitoring. The proposed system integrates smart attendance, power monitoring, automatic lighting control, and environmental sensing into a unified architecture using ESP32 microcontrollers and a Raspberry Pi embedded server. Attendance is automated using radio frequency identification (RFID), fingerprint recognition, and non-contact body temperature measurement, achieving an average accuracy of 92.5% with a system latency of 1.1–1.4 s. Electrical monitoring using the PZEM-004T sensor shows zero error for voltage and current measurements and a maximum power measurement error of 0.31%, while overload and abnormal voltage conditions are successfully handled through automatic protection. Automatic lighting control based on YOLOv5s image processing achieves approximately 90% detection accuracy under high occupancy conditions. All subsystems communicate via the message queuing telemetry transport (MQTT) protocol and are visualized through a real-time web dashboard. The results demonstrate that the proposed system provides a low-cost, scalable, and reliable solution for energy-efficient and intelligent classroom management in vocational education environments.

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1. INTRODUCTION

In the era of rapidly evolving digital technology, interconnected systems have significantly transformed various sectors, including industry, public services, and education [1], [2]. Modern educational environments increasingly rely on data-driven platforms and networked technologies to enhance operational efficiency, learning quality, and facility management [3]. Consequently, the education sector requires learning ecosystems that are not only interactive but also adaptive and technology-oriented. Emerging technologies such as the internet of things (IoT), embedded systems, artificial intelligence (AI), and cloud computing have become key enablers in the development of next-generation educational infrastructures [4], [5]. Through the integration of sensors, smart devices, and real-time data communication, classrooms can evolve into intelligent environments that support pedagogical effectiveness while optimizing resource utilization. Early implementations of IoT-based smart classrooms in Indonesian vocational institutions demonstrate this potential; however, these systems remain limited in functionality and integration [6]-[8].

As learning activities become more dynamic, the demand for intelligent classroom management systems that support energy efficiency, automation, and real-time monitoring continues to increase [9]. A smart classroom is no longer merely a digital learning space, but a cyber-physical system that integrates sensors, actuators, microcontrollers, and embedded servers to autonomously manage classroom operations. Such systems enable automated attendance, environmental monitoring, and intelligent control of electrical loads such as lighting and air conditioning based on occupancy and contextual information [10]. Despite these advancements, many vocational education institutions in Indonesia, including Politeknik Negeri Malang, Kediri Campus, still rely on manual classroom management. Attendance processes remain vulnerable to manipulation, electrical devices are often left operating unnecessarily, and environmental and electrical conditions are not continuously monitored.

These limitations increase the risk of excessive energy consumption, suboptimal learning conditions, and potential damage to electronic equipment caused by voltage instability or electrical overload [11]. In addition, most existing attendance systems do not incorporate basic health indicators, such as body temperature, which has become increasingly important in post-pandemic learning environments [12]. The absence of integrated monitoring for temperature, humidity, ultraviolet (UV) exposure, and electrical parameters highlights the lack of a holistic and adaptive classroom control system capable of responding to real-time conditions.

Previous studies have mainly addressed smart classroom components in isolation. Some researchers proposed attendance systems using facial recognition and radio frequency identification (RFID), but reported limitations related to lighting conditions, camera accuracy, and processing reliability [13]. Other studies employed motion sensors and cameras without integrating automatic device control or centralized data management [14]. Environmental monitoring systems using digital humidity and temperature (DHT)-series sensors have also been reported [15], while electrical monitoring using PZEM-004T sensors was generally limited to passive observation without automation or cloud-based visualization [16]. Although message queuing telemetry transport (MQTT) is recognized as a lightweight and efficient protocol for real-time IoT communication [17], it is rarely implemented as the core communication framework of an integrated classroom system.

To address these gaps, this study proposes a smart classroom 4.0 system that integrates attendance automation, energy monitoring, environmental sensing, and intelligent lighting control into a single embedded IoT architecture. The system combines ESP32 and Raspberry Pi platforms, utilizes MQTT for real-time communication, and provides cloud-based visualization through Firebase. Unlike previous works, this research delivers a low-cost, scalable, and unified smart classroom prototype that has been implemented and evaluated at Politeknik Negeri Malang, Kediri Campus. The proposed system offers a practical reference for accelerating digital transformation in vocational education institutions across Indonesia.

2. THE PROPOSE METHOD

In this research, an integrated smart class system based on the IoT and embedded technologies is proposed to enhance the efficiency and quality of the learning process in vocational classrooms. As illustrated in Figure 1, the system integrates four main modules: smart attendance, environmental monitoring, power monitoring, and automatic lighting control. The ESP32 microcontroller serves as the primary processing unit for data acquisition and sensor management, including the DHT22 sensor for temperature and humidity, the MLX90614 sensor for non-contact body temperature measurement, the PZEM-004T sensor for voltage and current monitoring, and the GUVA-S12SD sensor for UV light intensity detection [18]-[20]. The smart attendance module combines an RC522 RFID reader, an AS608 fingerprint sensor, and the MLX90614 temperature sensor to record student attendance while simultaneously performing basic health screening [21], [22].

Meanwhile, automatic lighting control is implemented based on real-time occupancy detection using a USB camera connected to a Raspberry Pi 4, where image data are processed using the YOLOv5s object detection algorithm integrated with the OpenCV library [23], [24]. All sensor and control data are transmitted using the MQTT communication protocol to a Firebase Realtime Database and visualized through a web-based interface hosted locally on the Raspberry Pi [25]. This architecture enables real-time monitoring and control of classroom conditions, both locally and remotely, as depicted in the system flowchart in Figure 2.

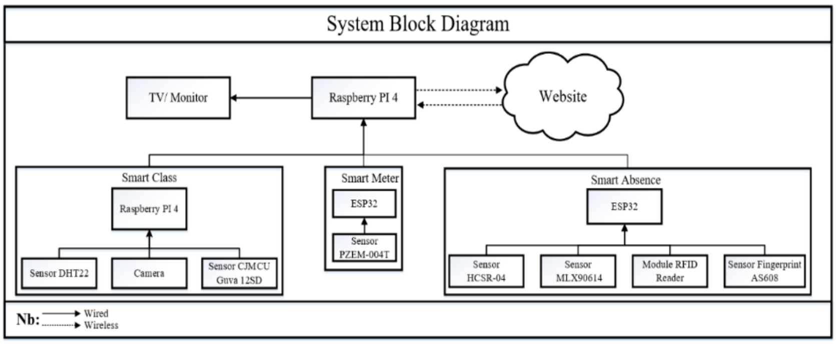


Figure 1. System block diagram

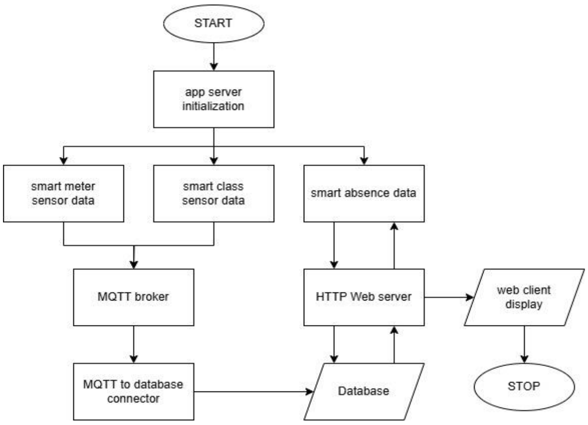


Figure 2. Flowchart system

3. MATERIAL AND METHOD

This chapter describes the method and system design used in the research. The system was developed with an embedded system and IoT based approach, which includes the design of hardware, software, and integration of various key features.

3.1. System hardware architecture

The smart class system developed consists of various hardware components that are designed in an integrated manner to be able to perform monitoring and control functions automatically. Table 1 here summarises the list of major components used in the construction of the system.

Table 1. Some of the components used in the system

Component	Function
ESP32	Microcontroller to control sensors and actuators in smart meter and smart attendance
Raspberry Pi 4	Microcontroller in smart class system and visual data processor
Camera USB	Used for indoor human presence detection
Sensor DHT22	Measuring room temperature and humidity
Sensor MLX90614	Measuring non-contact human body temperature
Sensor GUVA-S12SD	Measuring the intensity of UV light
Sensor PZEM-004T	Measure voltage, current and power of room electricity
Modul RFID RC522	Used for attendance identification (ID) using RFID cards
Sensor fingerprint AS608	Identity verification through biometrics
Modul relay 2 channel	Controlling actuators in the system
LCD 20x4 I2C	Display system local data in real-time

3.2. System software architecture

The smart class system shown in Figure 3 is equipped with an interactive web interface designed to display all monitoring and control data in real-time. This interface was developed using the Flask framework running on a Raspberry Pi 4 as a local server, and sending data using the MQTT protocol to the server. The system dashboard is divided into three main segments: smart meter, smart class, and smart absence, each of which provides a representation of important information from different subsystems.

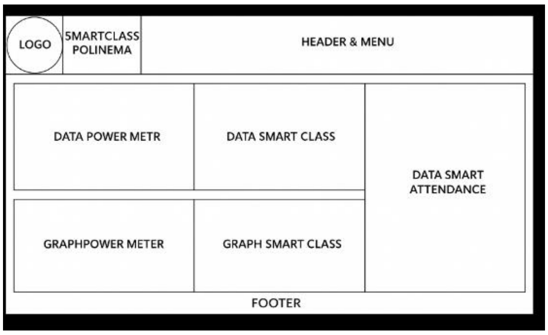


Figure 3. Template dashboard web

3.3. Smart meter system method

The system operation begins with the measurement of electrical parameters, including voltage, current, and power, using the PZEM-004T sensor. The acquired data are evaluated by the ESP32 to determine whether the operating conditions remain within predefined normal limits; if so, the data are processed and transmitted to the liquid crystal display (LCD) and web server for real-time visualization. When abnormal conditions are detected such as overload, under-voltage, over-voltage (with a threshold of 240 V), or a load approaching the maximum limit the system classifies the disturbance and initiates an appropriate response. In over-voltage or under-voltage conditions, the buzzer and speaker are activated as warning indicators and the relay disconnects the load to ensure electrical protection, whereas near-maximum load conditions trigger only an audio warning. Throughout all operating states, measurement data continue to be transmitted to both local and online interfaces, with automatic retransmission performed in the event of communication failure to maintain continuous and reliable monitoring.

3.4. Smart attendance system method

In attendance mode, students can choose between two methods: fingerprint-based attendance or RFID card attendance. For fingerprint attendance, the student places a finger on the fingerprint sensor; if the fingerprint ID is recognized and registered in the database, the student’s name, ID number, and class are displayed on the LCD, otherwise a retry message is shown. For the RFID method, the student taps the student card on the RFID sensor, and if the card is registered, the same information is displayed, while unregistered cards trigger a warning message. After successful identification, the system performs body temperature screening by activating an ultrasonic sensor to detect the student at a distance of less than 5 cm, followed by temperature measurement using the MLX90614 sensor. If the temperature exceeds 37.5°C, the LCD displays a high-temperature warning, the red light emitting diode (LED) turns on, and the speaker announces an alert; otherwise, the attendance data are transmitted to the website, and a confirmation message indicating successful attendance is shown on both the LCD and the web interface.

3.5. Smart class system method

The smart class system integrates automatic lighting control based on classroom occupancy with environmental monitoring of temperature, humidity, and UV light intensity. Occupancy detection is performed using a USB camera connected to a Raspberry Pi 4 running the YOLOv5s algorithm, enabling adaptive lighting control and automatic lamp deactivation during periods of inactivity to enhance energy efficiency. Environmental parameters are measured using a DHT22 sensor for temperature and humidity and a GUVA-S12SD sensor for UV intensity. All sensor data are transmitted via the MQTT protocol and visualized on a web-based dashboard in real time.

UV intensity monitoring is implemented based on standard UV index (UVI) reference values, where indoor environments are classified as safe at UVI < 2, require caution at UVI levels of 3–5, and may pose health risks at UVI > 6 due to potential eye and skin exposure. By continuously monitoring UV levels and maintaining them within safe thresholds, the system supports visual comfort, protects occupant health, and evaluates the contribution of natural sunlight to indoor illumination. This integrated approach contributes to the creation of a healthier, safer, and more effective learning environment.

3.6. Embedded system communication method

The communication architecture of the proposed system enables seamless integration of all subsystems namely smart meter, smart attendance, and smart class within a unified embedded IoT ecosystem. These subsystems are connected to a centralized embedded server hosted on a Raspberry Pi, which operates as both the MQTT broker and the data management server. In the smart meter and smart attendance subsystems, ESP32 microcontrollers function as data acquisition and processing units and are connected to the local network via W5500 Ethernet modules to ensure stable, low-latency, and reliable communication. Sensor data are transmitted to the embedded server in real time using the MQTT protocol, selected for its lightweight architecture, low communication overhead, and suitability for constrained local network environments.

To efficiently manage data exchange, a hierarchical MQTT topic structure is implemented to clearly separate subsystems, devices, and data types. Top-level topics represent each subsystem (e.g., smartmeter, attendance, and smartclass), followed by device identifiers and specific parameters such as voltage, power, occupancy count, temperature, and attendance status. For instance, smart meter data are published under topics such as smartmeter/room1/voltage and smartmeter/room1/power, while attendance and classroom monitoring data use topics such as attendance/class4A/status and smartclass/room1/occupancy. The Raspberry Pi server subscribes to all relevant topics, processes incoming messages, stores them in the database, and forwards the information to the web-based dashboard for real-time visualization. This structured topic hierarchy enhances system scalability, simplifies data management, and ensures reliable real-time communication across all subsystems within the smart classroom environment.

4. RESULTS AND DISCUSSION

This section presents the implementation results and performance evaluation of the proposed IoT-based smart class system, which consists of four main subsystems: smart meter, smart attendance, smart class, and the web-based dashboard. Each subsystem is evaluated based on functional performance, sensor accuracy, system responsiveness, and reliability under real classroom operating conditions.

The evaluation results cover the system’s capability to monitor and control electrical power consumption, automate attendance using biometric identification and non-contact body temperature measurement, regulate classroom lighting based on human occupancy detection, and monitor environmental parameters. All sensor data are transmitted to the server in real time using the MQTT protocol and visualized through an integrated web dashboard. This discussion assesses the effectiveness of the proposed system in enhancing energy efficiency, automation, and digital transformation within vocational classroom environments.

4.1. Hardware implementation result

The smart class system was implemented and tested in a single classroom located in the Automation Laboratory. The smart meter module was installed at the rear of the classroom, while the smart attendance system was positioned near the entrance to facilitate student access. The smart class module, equipped with image processing capabilities, was mounted above the front whiteboard to enable real-time occupancy monitoring. The embedded control system was connected to the classroom’s electrical switchboard, allowing automated control of electronic devices. Data collected from all subsystems were transmitted in real time and displayed on a television installed in the building lobby, providing centralized monitoring of classroom conditions.

4.2. Testing smart meter

The smart meter system functions as a real-time monitoring unit of power consumption, voltage, and current using the PZEM-004T sensor integrated with the ESP32 microcontroller. Tests were conducted in two categories: accuracy of electrical parameter readings, and reliability of early warning and automatic protection systems.

4.3. Voltage, current and power accuracy testing

As presented in Table 2, this test evaluates the accuracy of the PZEM-004T sensor by comparing its measurements with those obtained from a digital multimeter. The evaluated parameters include voltage (V), current (A), and power (W). The results show that the voltage and current measurements from the system match the reference values exactly, resulting in zero measurement error and demonstrating excellent sensing accuracy. Minor deviations were observed in the power measurements, with errors ranging from 0.05% to 0.31%, which remain within acceptable limits for electrical monitoring applications. These findings confirm that the proposed system provides reliable and accurate real-time measurement of voltage, current, and power.

Table 2. Accuracy test results of PZEM-004T sensor

No	Parameter	Value multimeter	Value system	Error (%)
1	Voltage (V)	213 V	213 V	0
2	Voltage (V)	203 V	203 V	0
3	Voltage (V))	197 V	197 V	0
4	Ampere (A)	2.17 A	2.17 A	0
5	Ampere (A)	2.40 A	2.40 A	0
6	Ampere (A)	2.30 A	2.30 A	0
7	Power (W)	345.40 W	345.20 W	0.06
8	Power (W)	129.80 W	129.40 W	0.31
9	Power (W)	198.00 W	197.90 W	0.05

4.4. Testing early warning and protection features

The early warning and protection features of the system were evaluated to verify their reliability in handling abnormal operating conditions, including overloads and voltage fluctuations. The tests involved key components such as the buzzer, DFPlayer with speaker, LCD, and relay-based protection. Each component was assessed against predefined threshold values to determine the system’s ability to deliver timely warnings and execute appropriate protective actions. The outcomes of these evaluations are summarized in Table 3.

Table 3. Testing results of early warning and protection features

No	Component	Test condition	Parameter / threshold	System response
1	Buzzer	Total overload	Total power ≥ 3000 W	Buzzer active, all outputs OFF
2	Buzzer	Overload on Table 1 / Table 2	Power ≥ 1500 W	Buzzer active after 10 seconds
3	Buzzer	Abnormal voltage	Voltage < 198 V / > 242 V	Buzzer active, all outputs OFF
4	DFPlayer + speaker	Overload / abnormal voltage detection	Response < 1 second	Audio automatically plays based on condition
5	DFPlayer + speaker	Audio clarity and stability test	Clear sound and stable playback	Suitable for classroom use, no disturbance
6	DFPlayer + speaker	UART communication test with ESP32	GPIO14 and GPIO27	Works smoothly, commands executed successfully
7	LCD	Overload or near maximum load	Tables 1/2 Power > 1200–1500 W	Displays warning based on load
8	LCD	High / low voltage	Input > 242 V / < 198 V	Displays “Over” / “Down” warning
9	LCD	Normal condition	Voltage and power within limits	Displays real-time current and power of Tables 1 and 2
10	Relay (protection)	Low voltage (08:00)	158 V	Relay OFF (disconnected), protection active
11	Relay (protection)	High voltage (10:00)	250 V	Relay OFF (disconnected), protection active
12	Relay (protection)	Table overload (11:00)	1500 W	Relay OFF (disconnected), protection active

The test results demonstrate that the proposed smart control system effectively prevents excessive energy consumption by automatically disconnecting electrical loads during overload and abnormal voltage conditions. By enforcing power thresholds of 1200–1500 W per table and a maximum total load of 3000 W, the system eliminates unnecessary power usage that could occur if equipment continued operating under unsafe conditions. Compared with conventional systems lacking automatic protection, this intelligent control strategy reduces energy waste during peak load and fault scenarios through timely relay disconnection and warning activation. Overall, the integration of buzzer alerts, automatic relay cutoff, and real-time monitoring enhances electrical safety, improves system reliability, and contributes to measurable energy savings.

4.5. Testing smart absence

This section presents the testing and performance evaluation of the fingerprint sensor, RFID sensor, and MLX90614 temperature sensor, as summarized in Tables 4 to 6. The fingerprint sensor results in Table 4 indicate variations in accuracy and response time depending on the finger used. The index and middle fingers achieved the highest accuracy (90%) with faster response times, whereas the little finger exhibited lower accuracy and slower response, primarily due to its smaller contact area and higher positioning sensitivity. As shown in Table 5, the RFID sensor demonstrated stable and rapid detection with a consistent response time of 0.5 s at distances up to 4 cm. Detection failed at a distance of 5 cm, confirming the effective operational range of the RFID module. Furthermore, the MLX90614 temperature sensor results in Table 6 show high accuracy at close measurement distances, with a minimal error of 1.3% at 1 cm. However, the measurement error increased as the distance grew, which can be attributed to infrared signal dispersion and environmental interference.

In Table 7 is the result of testing the entire system, it can be seen from the number of samples of 6 students, 5 students are fingerprints that have been registered and 1 student whose finger is being wound to identify data using RFID that has been registered to identify user data when taking temperature measurements. The results show that the system successfully recorded attendance and body temperature data for all students in real time, with measured temperatures remaining within the normal physiological range. The sensor-to-dashboard latency ranged from 1.1 to 1.4 seconds, indicating fast and stable data transmission suitable for classroom monitoring applications.

Table 4. Fingerprint sensor testing results

No	Finger	Response	Accuracy (%)	Response time (s)
1	Thumb	Valid	70	1
2	Index	Valid	90	0.9
3	Middle	Valid	90	0.9
4	Ring	Valid	60	1.2
5	Little	Valid	40	1.3

Table 5. RFID sensor testing results

No	Distance (cm)	Test 1	Test 2	Test 3	Test 4	Response time (s)	Description
1	1	✓	✓	✓	✓	0.5	Read
2	3	✓	✓	✓	✓	0.5	Read
3	4	X	✓	✓	✓	0.5	Read
4	5	X	X	X	X	0.5	can not be read

Table 6. MLX90614 sensor testing results

No	Distance (cm)	Thermogun (°C)	Sensor MLX90614 (°C)	Error (%)
1	1	36.3	35.8	1.3
2	2	36.3	34.3	5.5
3	3	36.2	34.2	5.5
4	4	36.2	33.6	7.4
5	5	36.2	33.1	8.5

Table 7. System smart absence testing results

No	Name	Course	Class	Temp (°C)	Date	Time (WIB)	Status	System latency (s)
1	Nizar Fairuzaman	Scientific writing methodology	4A	36.2	Thursday, 15/5/2025	16:24	Present	1.2
2	Picca Dwi Chandra	Scientific writing methodology	4A	36.3	Thursday, 15/5/2025	16:40	Present	1.4
3	Ridwan Maulana	Scientific writing methodology	4A	36.3	Thursday, 15/5/2025	16:38	Present	1.3
4	Septian Eko Nurcahyo	Scientific writing methodology	4A	36.2	Thursday, 15/5/2025	16:23	Present	1.1
5	Zidan Aksa Mahendra	Scientific writing methodology	4A	36.2	Thursday, 15/5/2025	16:37	Present	1.3

4.6. Testing smart class control

The testing of the smart class subsystem was conducted to evaluate the accuracy of the DHT22 sensor in measuring temperature and humidity, as well as to assess the effectiveness of the automatic lighting control system based on occupant detection, as illustrated in Figure 4. The DHT22 sensor demonstrated reliable performance by providing stable and consistent readings when compared with a reference thermometer, confirming the accuracy of the environmental monitoring component. In addition, the automatic lighting control system was evaluated by varying the number of occupants in the classroom. The Raspberry Pi–based image processing successfully detected the number of individuals present and adjusted the lamp status accordingly.

The threshold logic for automatic lighting control was defined based on occupancy levels detected by the camera. When two or more occupants were identified, both Lamp 1 and Lamp 2 were automatically activated to ensure sufficient and evenly distributed illumination. This threshold strategy was designed to adapt lighting intensity to real-time classroom occupancy, thereby improving energy efficiency while preventing unnecessary power consumption. Overall, the results indicate that the proposed detection and automatic control mechanism operated reliably, maintaining acceptable accuracy and stable performance even as the number of detected occupants increased.

```
{
  "temperature": 25.5,
  "humidity": 67.6,
  "uv_status": "Not Detected",
  "people_count": 10,
  "lamp_status": "Lamp 1 & 2 ON",
}
```

Figure 4. Image processing detection on system

To further evaluate the robustness and scalability of the smart class subsystem, additional experiments were conducted involving larger student groups and multiple classroom environments. These tests assessed the performance of the YOLO-based people detection algorithm under high occupancy density and varying spatial conditions, as well as the reliability of the automatic lighting and attendance mechanisms. As summarized in Table 8, when the number of students increased from 20 to 40 individuals in a single classroom, the camera-based detection system consistently achieved detection accuracies close to 90%. Minor accuracy degradation was observed at higher occupancy levels, primarily due to occlusion, overlapping body positions, and limitations in the camera field of view. Nevertheless, the automatic lighting control system responded correctly in all test scenarios, activating Lamp 1 and Lamp 2 whenever the predefined occupancy threshold was reached.

To further examine scalability, the system was deployed in three classrooms with different sizes and lighting conditions, as presented in Table 9. The detection accuracy in all classrooms exceeded 90%, with slight variations attributed to differences in camera placement, room geometry, and ambient illumination. Despite these environmental variations, the lighting control mechanism operated reliably, confirming the adaptability of the proposed system for multi-room smart classroom deployments.

Quantitative evaluation of the YOLO-based detection model showed a precision of 92.3%, a recall of 89.1%, and an F1-score of 90.7%, indicating robust detection performance with a low false-positive rate and effective identification of occupants under crowded conditions. Moreover, a comparison between the proposed system and conventional manual attendance revealed a significant improvement in operational efficiency. While manual attendance achieved 100% accuracy but required 5–10 minutes per session, the automated system achieved an average attendance accuracy of 92.5% with a processing time of less than one minute. Although the automated approach exhibits a slight reduction in accuracy due to occlusion and detection overlap, it provides substantial time savings and improved scalability for real-time classroom management.

Table 8. Smart class testing with larger student groups (single classroom)

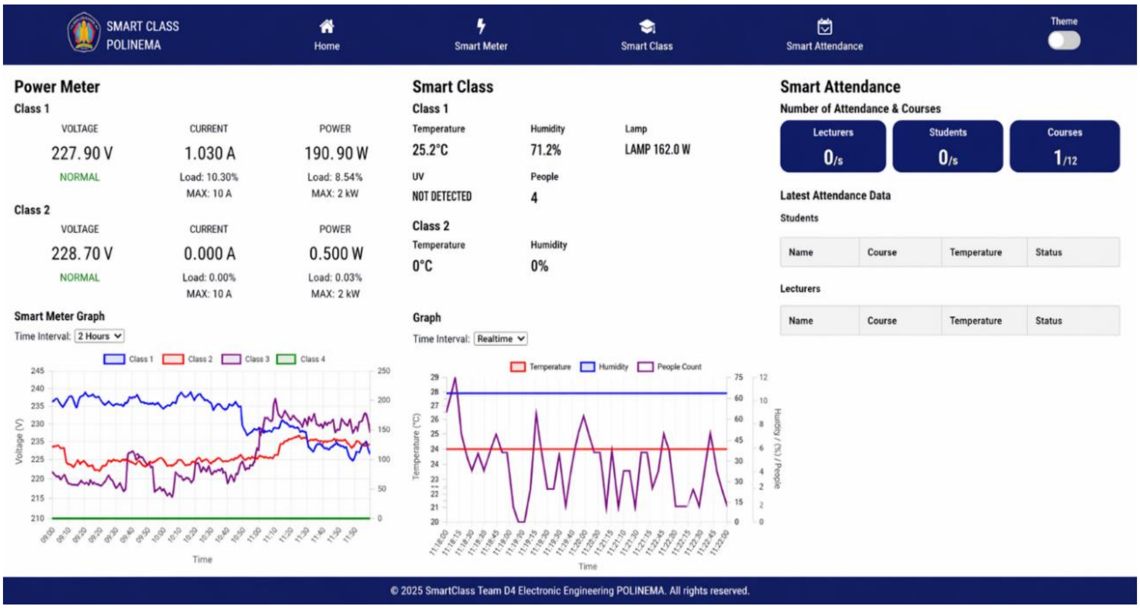
No	Actual number of students	Detected by camera	Detection accuracy (%)	Lamp status
1	20	18	90	Lamp 1 and 2 ON
2	25	22	88	Lamp 1 and 2 ON
3	30	27	90	Lamp 1 and 2 ON
4	35	31	88.6	Lamp 1 and 2 ON
5	40	36	90	Lamp 1 and 2 ON

Table 9. Multi-classroom occupancy detection results

Classroom	Actual occupancy	Detected occupancy	Accuracy (%)	Lighting response
Class A	18	17	94.4	Lamp 1 and 2 ON
Class B	24	22	91.7	Lamp 1 and 2 ON
Class C	32	29	90.6	Lamp 1 and 2 ON

4.7. Testing dashboard website

The web-based dashboard was tested to validate its ability to provide real-time visualization and centralized control of the smart classroom ecosystem. As shown in Figure 5, the dashboard is divided into several panels, each representing a different subsystem. On the left side, the power meter panel displays real-time data of voltage, current, and power consumption for two classrooms, accompanied by a time-series graph that records historical energy usage.



Power Meter

Class 1

VOLTAGE	CURRENT	POWER
227.90 V	1.030 A	190.90 W
NORMAL	Load: 10.30% MAX: 10 A	Load: 8.54% MAX: 2 kW

Class 2

VOLTAGE	CURRENT	POWER
228.70 V	0.000 A	0.500 W
NORMAL	Load: 0.00% MAX: 10 A	Load: 0.03% MAX: 2 kW

Smart Meter Graph

Time Interval: 2 Hours

Smart Class

Class 1

Temperature: 25.2°C
Humidity: 71.2%
Lamp: LAMP 162.0 W
UV: NOT DETECTED
People: 4

Class 2

Temperature: 0°C
Humidity: 0%

Graph

Time Interval: Realtime

Smart Attendance

Number of Attendance & Courses

Lecturers	Students	Courses
0/s	0/s	1/12

Latest Attendance Data

Students

Name	Course	Temperature	Status

Lecturers

Name	Course	Temperature	Status

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Figure 5. Dashboard website

This feature enables administrators to monitor electrical performance and detect anomalies such as sudden voltage spikes or drops. In the central section, the smart class panel displays environmental monitoring data, including room temperature, humidity, and the operational status of actuators such as lighting systems. Human presence detection results are also presented, supported by graphical trend analyses of environmental parameters and occupancy activity. This visualization allows the system to automatically adapt to real-time classroom conditions while maintaining transparency for manual supervision.

On the right side of the interface, the Smart Attendance panel shows the number of students and lecturers detected during a class session, along with the most recent attendance records stored in the database. This functionality enables real-time validation of attendance data, thereby improving accuracy and reducing the potential for manipulation. During system testing, the dashboard successfully displayed integrated data from all three subsystems with an update interval of approximately one second. The interface remained responsive across multiple devices and demonstrated stable performance under varying network conditions. These results confirm that the dashboard provides comprehensive classroom monitoring and functions as an effective decision-support tool for administrators in managing energy consumption, attendance, and environmental quality.

5. CONCLUSION

This research successfully designed and implemented a smart classroom 4.0 system based on IoT and embedded technologies, integrating attendance automation, electrical monitoring, environmental sensing, and intelligent lighting control within a unified embedded ecosystem. Experimental results demonstrate that the electrical monitoring subsystem utilizing the ESP32 and PZEM-004T sensor achieved high measurement accuracy, with 0% error for voltage and current readings and power measurement errors ranging from 0.05% to 0.31%. The system reliably detected abnormal electrical conditions and automatically disconnected loads during overvoltage (>242 V), undervoltage (<198 V), and overload conditions (>1500 W per table), thereby improving electrical safety and reducing unnecessary energy consumption. The smart attendance subsystem, which integrates RFID, fingerprint recognition (AS608), and non-contact temperature sensing (MLX90614), operated effectively in real classroom conditions. Fingerprint recognition achieved a maximum accuracy of

90% for index and middle fingers, while lower accuracy (40%) was observed for little fingers, indicating sensitivity to finger placement and contact area. The RFID system maintained a stable response time of 0.5 s at distances up to 4 cm. The MLX90614 temperature sensor exhibited minimal error at close range (1.3% at 1 cm), although the error increased to 8.5% at a distance of 5 cm. Overall system latency from sensor acquisition to web dashboard visualization ranged between 1.1 and 1.4 s, confirming real-time performance.

The vision-based lighting control subsystem, implemented using YOLOv5s on a Raspberry Pi 4, achieved strong detection performance with a precision of 92.3%, recall of 89.1%, and an F1-score of 90.7%. Automatic lighting control functioned reliably across varying occupancy levels and classroom environments. Compared to manual attendance methods, the proposed system reduced attendance time from 5–10 minutes to less than one minute, despite a slight reduction in accuracy. System limitations include reduced fingerprint reliability for certain finger types, increased temperature measurement error at longer distances, and decreased detection accuracy under crowded conditions due to occlusion. Future research should focus on advanced sensor fusion, improved calibration techniques, higher-resolution vision systems, and predictive energy management algorithms to enhance scalability and support large-scale smart campus implementations.

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This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Septriandi Wirayoga	✓	✓		✓	✓			✓	✓			✓		✓
Nizar Fairuzaman		✓	✓	✓		✓		✓	✓		✓			✓
Moh Muzib Pratama	✓	✓		✓		✓	✓			✓	✓		✓	✓
Wildan Ahmad Fauzi		✓	✓	✓	✓		✓			✓	✓			✓
Mohammad Alwi Ferdiansyah Alfarizi	✓	✓	✓		✓			✓	✓			✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no known conflict of interest, either financial or personal, that could influence the outcome of this research.

INFORMED CONSENT

Informed consent was obtained from all individuals involved in the evaluation and testing phases of this study.

ETHICAL APPROVAL

This research did not involve animal or human subjects requiring formal ethical approval from an institutional review board.

DATA AVAILABILITY

All data supporting the findings of this study are available within the manuscript and/or in its supplementary materials. Additional data may be provided upon reasonable request to the corresponding author.

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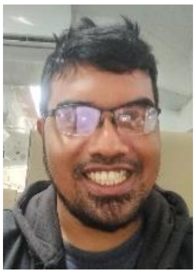
BIOGRAPHIES OF AUTHORS



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