Linear Calibration Modelling of The BME280 Sensor for Accurate Environmental Data Acquisition

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Abstract. Environmental monitoring systems require accurate measurements of temperature, humidity, and air pressure to support reliable data analysis and decision-making. The BME280 sensor, developed by Bosch Sensortec, is widely used in Internet of Things (IoT) applications due to its compact design and low power consumption. However, sensor readings may drift over time, necessitating calibration to ensure validity. This study presents a linear calibration modelling approach for the BME280 sensor integrated with NodeMCU ESP32 Microcontroller and a P10 display panel. Calibration was performed by comparing sensor outputs with reference instruments, followed by regression-based correction modelling. Results demonstrated high accuracy: 98.24% for temperature, 98.37% for humidity, and 99.91% for air pressure, alongside excellent precision and low bias values. The findings confirm that linear calibration modelling significantly enhances the reliability of BME280-based environmental monitoring systems.

Keywords: Environmental monitoring, BME280 sensor, calibration modelling, NodeMCU ESP32, regression-based correction.

1 Introduction

Environmental monitoring has become an indispensable aspect of modern life, encompassing diverse fields such as meteorology, agriculture, industrial management, and residential comfort systems. Accurate measurement of environmental parameters, particularly temperature, humidity, and air pressure, is essential for ensuring safety, optimizing processes, and supporting data-driven decision-making [1]. Sophisticated systems such as Automated Weather Observing Systems (AWOS) are widely employed to collect meteorological data in real time, integrating multiple sensors, data loggers, and communication modules to provide reliable information for aviation, weather forecasting, and disaster preparedness [2]. However,

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despite their reliability, such systems are often costly, complex, and limited to institutional use, leaving a gap for more accessible and affordable monitoring solutions [3].

The rapid advancement of Internet of Things (IoT) technologies has opened new opportunities to design compact, low-cost, and efficient monitoring devices [4][5]. Microcontrollers such as the NodeMCU ESP32 have become central to this development, offering built-in Wi-Fi and Bluetooth connectivity, low power consumption, and versatile programming environments [6]. When paired with environmental sensors, these microcontrollers enable real-time data acquisition, storage, and transmission to web-based platforms, allowing users to monitor conditions remotely [7]. This integration democratizes access to environmental data and supports applications in smart agriculture, indoor air quality management, and community-based weather stations [8].

Among the various sensors available, the Bosch BME280 has emerged as a popular choice due to its multifunctional capabilities [9]. The BME280 is a digital sensor capable of simultaneously measuring temperature, humidity, and air pressure with high resolution and low energy consumption [10]. Its compact size and compatibility with both I2C and SPI communication protocols make it suitable for portable and battery-powered IoT devices [11]. Nevertheless, like most sensors, the BME280 is subject to measurement drift caused by environmental factors, aging, and manufacturing tolerances [12]. Over time, these deviations can compromise the accuracy of collected data, leading to unreliable analyses and potentially flawed decisions [13].

Calibration is therefore a critical step in ensuring the validity of sensor-based measurements [14]. It refers to the process of adjusting sensor outputs so that they align with reference instruments or known standards. Without calibration, even advanced sensors may produce biased or inconsistent readings [15]. In environmental monitoring, uncalibrated data can misrepresent actual conditions, for instance underestimating humidity levels in agricultural applications or misreporting air pressure in meteorological studies [7]. Such inaccuracies highlight the importance of implementing systematic calibration procedures.

Linear regression modelling offers a practical and effective approach to sensor calibration. By establishing a mathematical relationship between sensor readings and reference values, linear regression enables the derivation of correction formulas that can be embedded directly into microcontroller programs. This method reduces bias and enhances accuracy and precision, ensuring that sensor outputs remain consistent across repeated measurements. In the case of the BME280, linear calibration modelling can significantly improve its performance, making it a reliable tool for environmental data acquisition in IoT-based systems [13][15].

Previous studies have explored various sensor and microcontroller combinations, such as ATmega328P with DHT22, NodeMCU ESP8266 with SHT75, and hybrid systems using DHT11 and BMP085. While these systems demonstrated promising results, they often lacked comprehensive pressure measurement or suffered from calibration limitations. Other research integrating display panel P10 for air quality visualization showed potential for public engagement but did not incorporate real-time calibration modelling [9]. Building on these findings, this study leverages the ESP32 microcontroller, the BME280 sensor, and a P10 display panel to design a calibrated monitoring system that addresses these gaps.

This research focuses on the design and implementation of linear calibration modelling for the BME280 sensor integrated with NodeMCU ESP32 and a P10 display panel. The system is intended to provide accurate, real-time monitoring of temperature, humidity, and air pressure, with data displayed locally and transmitted to a web-based database for remote access. By applying regression-based correction formulas derived from reference instruments, the study aims to enhance the reliability of sensor readings. Ultimately, this work contributes to the development of affordable, accessible, and trustworthy IoT-based monitoring systems that can complement institutional infrastructures and empower communities to engage in environmental observation.

2 Methodology

The methodology of this study was designed to ensure that the calibration process of the BME280 sensor could be carried out systematically, producing reliable correction models for accurate environmental data acquisition. The research was conducted in the Electronics Laboratory of the Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, in 2025. The methodological framework consisted of several stages: preparation of tools and materials, system design, calibration procedure, data acquisition, and statistical analysis.

The hardware components included a NodeMCU ESP32 microcontroller, which served as the central processing unit for data acquisition and transmission. The BME280 sensor was used to measure temperature, humidity, and air pressure simultaneously. A P10 LED display panel was integrated into the system to provide real-time visualization of sensor readings. Additional components such as a breadboard, jumper cables, soldering tools, and a regulated 5V power supply facilitated circuit assembly.

On the software side, Arduino IDE was used to program the ESP32 and implement calibration formulas. Visual Studio Code and XAMPP were employed to develop and test a web-based monitoring interface, while Microsoft Excel was utilized for statistical analysis, regression modelling, and visualization of calibration curves.

The environmental monitoring system was designed to acquire data from the BME280 sensor and process it using the NodeMCU ESP32 microcontroller, as illustrated in **Figure 1**. The sensor, connected via the I2C interface, continuously measured temperature, humidity, and air pressure, transmitting raw data to the ESP32 for processing. Within the microcontroller, calibration formulas derived from regression modelling were embedded to automatically correct sensor outputs, ensuring that the displayed values were accurate and reliable. The corrected data were subsequently transmitted to a P10 LED display panel, which provided real-time visualization of environmental parameters for local monitoring. To maintain stable operation, the system was powered by a regulated 5V supply, while supporting components such as jumper cables, breadboards, and connectors facilitated circuit integration. The program controlling the system was developed using the Arduino IDE, incorporating routines for library initialization, time synchronization, and calibration implementation. The workflow followed a structured cycle: system initialization, acquisition of sensor data, application of calibration formulas, display of corrected values on the P10 panel, and repetition of the process at five-second intervals. This design ensured continuous operation of the monitoring system, delivering accurate and real-time information on environmental conditions without reliance on external storage or complex infrastructure.

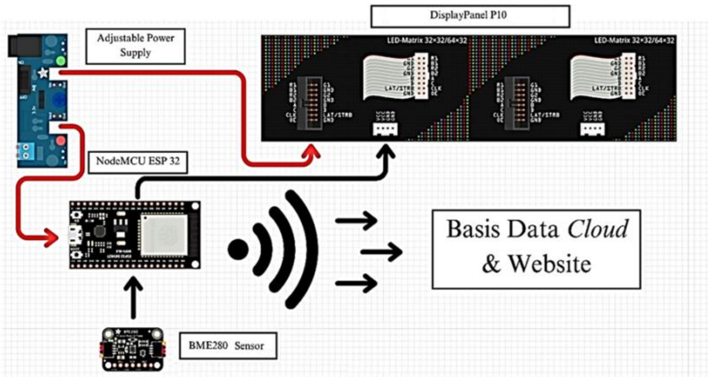

Fig. 1. Hardware circuit configuration for environmental monitoring using BME 280 sensor and NodeMCU ESP32 microcontroller

Calibration was performed by comparing sensor readings with reference instruments that had been factory-calibrated. For each parameter temperature, humidity, and air pressure measurements were taken in controlled laboratory conditions. Each measurement was repeated ten times to minimize random errors and ensure consistency.

The calibration process followed these steps:

1. Sensor Initialization: The BME280 was connected to the ESP32 and programmed to record raw data.
2. Reference Measurement: Simultaneous readings were taken using standard thermometers, hygrometers, and barometers via local weather station. Temperature and humidity standard were measured using a digital thermohygrometer (Thermometer TP-50) equipped with a calibration certificate issued by the National Accreditation Committee of Indonesia (Komite Akreditasi Nasional, KAN), ensuring compliance with internationally recognized accuracy standards.
3. Data Collection: Sensor and reference values were recorded in parallel, producing datasets for each parameter.
4. Regression Modelling: Linear regression analysis was applied to establish correction formulas.
5. Implementation: The derived formulas were embedded into the ESP32 program, enabling automatic correction of sensor outputs.
6. Verification: Post-calibration readings were compared again with reference instruments to validate accuracy and precision.

The calibration process was evaluated using bias, accuracy, and precision metrics. Bias was calculated as the difference between sensor readings and reference values. Accuracy was determined using formulas that incorporated bias and standard deviation, while precision was assessed by analysing the consistency of repeated measurements. Regression coefficients and the coefficient of determination (R^2) were also calculated to evaluate the fit of the calibration models.

3 Results and Discussion

The calibration process of the BME280 sensor produced a series of results that highlight the effectiveness of linear regression modelling in improving measurement accuracy for environmental data acquisition. The raw sensor readings of temperature, humidity, and air pressure were initially compared with reference instruments, revealing small but consistent deviations. These deviations, often referred to as bias, are common in digital sensors due to manufacturing tolerances, environmental drift, and long-term usage. Without calibration, such biases could accumulate and lead to significant errors in applications where precise environmental monitoring is critical.

3.1 Calibration results for temperature

The calibration curve for temperature revealed a strong linear relationship between the sensor readings and the reference thermometer values. As shown in **Figure 2**, the scatter plot compares temperature measurements from a standard thermometer and a thermocouple, with each data point representing a paired observation. The fitted regression line follows the equation $y = 0.8279x + 5.4581$, and the coefficient of determination (R^2=0.9623) indicates that over 96% of the variation in thermocouple readings can be explained by the thermometer values. This high correlation confirms the consistency of the reference instruments and validates the calibration environment used in the study.

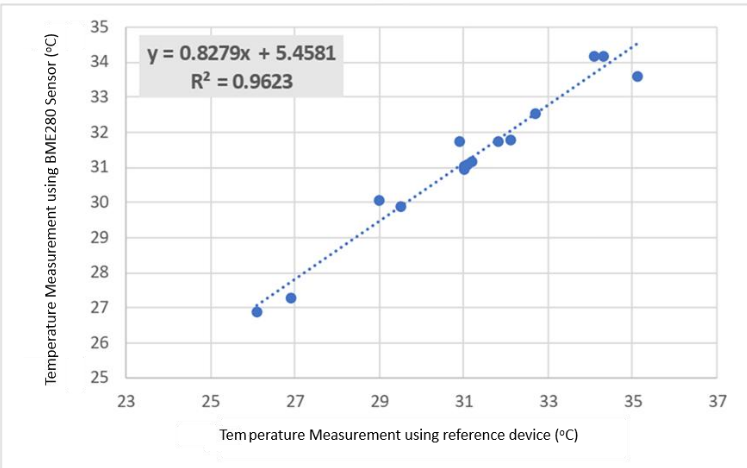

Fig. 2. Calibration curve modeling for temperature measurement

3.2 Calibration results for humidity

Humidity measurements often present greater challenges due to the sensitivity of sensors to environmental conditions such as condensation, airflow, and temperature fluctuations. In this study, the BME280 sensor initially exhibited slight inconsistencies when compared to the reference hygrometer, particularly at mid-range humidity levels. These deviations were most evident in transitional zones, where environmental instability could influence sensor response. However, after applying the linear regression calibration model, the sensor's performance improved significantly.

As shown in **Figure 3**, the scatter plot illustrates the relationship between the reference hygrometer readings and the BME280 sensor outputs. The fitted regression line follows the equation $y = 1.2027x - 19.078$, with a coefficient of determination $R^2 = 0.9565$. This high R^2 value indicates that approximately 95.65% of the variation in the calibrated sensor readings can be explained by the reference measurements, confirming the effectiveness of the calibration model in correcting systematic bias.

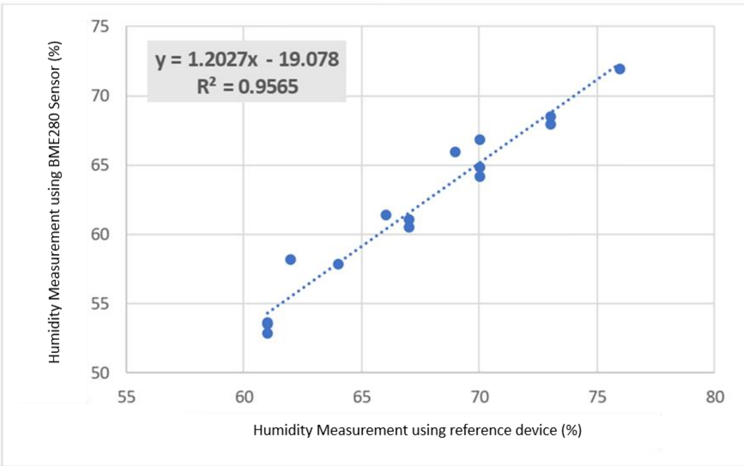

Fig. 3. Calibration Curve Modeling for Humidity Measurement

3.3 Calibration results for air pressure

Air pressure calibration yielded the most robust results among the three environmental parameters evaluated. The BME280 sensor demonstrated a strong linear relationship with the reference barometer, confirming its capability to produce accurate and consistent pressure measurements. As shown in Figure 4, the scatter plot illustrates the correlation between the sensor readings and reference values, with the fitted regression line following the equation $y = 1.1989x - 200.94$. The coefficient of determination ($R^2 = 0.9002$) indicates that approximately 90.02% of the variation in the calibrated sensor readings can be explained by the reference measurements. This high level of correlation validates the effectiveness of the linear calibration model in correcting systematic deviations.

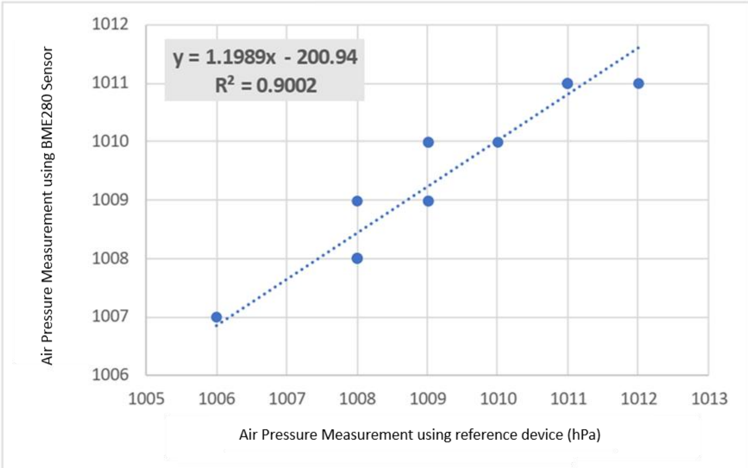

Fig. 4. Calibration Curve Modeling for Air Pressure Measurement

3.4 Model validation

The regression models for all three parameters produced high coefficients of determination (R^2), indicating that the linear calibration approach was well-suited to the sensor's behavior. As shown in **Table 1**, each model demonstrated a strong linear fit between the sensor readings and reference measurements, with R^2 values exceeding 0.90 across all cases. Bias values decreased substantially after calibration, while standard deviation values confirmed the consistency of repeated measurements. The combination of high accuracy, low bias, and strong precision demonstrates that the calibration process was successful in aligning sensor outputs with reference standards.

Table 1. Calibration Summary Table.

Measurement	Calibration Equation	R^2 (Coefficient of Determination)
Temperature	y = 0.8279x + 5.4581	0.9623
Humidity	y = 1.2027x − 19.078	0.9565
Air Pressure	y = 1.1989x − 200.94	0.9002

3.5 Discussion of sensor performance

The results highlight several important implications for environmental monitoring. First, calibration is essential for ensuring that sensor data is valid and trustworthy. Even small deviations in raw sensor readings can lead to incorrect conclusions, particularly in applications that rely on continuous monitoring and automated decision-making. In this study, the calibration process significantly enhanced the reliability of the BME280 sensor, as shown in **Table 2**. Regression accuracy percentage is obtained by calculating the relative deviation between predicted and observed values. The accuracy values achieved for temperature (98.24%), humidity (98.37%), and air pressure (99.91%) confirm that the sensor, once calibrated, can deliver measurements that closely align with reference standards.

Second, the effectiveness of linear regression modelling demonstrates that relatively simple statistical techniques can substantially improve sensor performance. The precision values obtained, 99.13% for temperature, 99.47% for humidity, and 100% for air pressure, indicate that the system consistently produces stable readings across repeated measurements. Moreover, the low bias values (0.27 °C for temperature, 0.74% RH for humidity, and 0.87 hPa for air pressure) suggest minimal deviation from reference instruments, reinforcing the validity of the calibration approach. These metrics collectively demonstrate that linear regression modelling is both practical and accessible, allowing researchers and practitioners to implement calibration without relying on complex algorithms or expensive equipment.

Third, the integration of calibration models directly into the NodeMCU ESP32 program ensures that corrected values are available in real time. This feature enhances the usability of the monitoring system, as users can access accurate data immediately through the P10 LED display panel. The ability to visualize calibrated environmental parameters locally supports rapid decision-making and situational awareness in various settings, such as laboratories, greenhouses, and indoor air quality monitoring. By embedding the calibration logic within the microcontroller, the system eliminates the need for post-processing or external correction, streamlining the data acquisition workflow.

Overall, the combination of high accuracy, excellent precision, and low bias, as shown in Table 2, confirms that the calibrated BME280 sensor system is a reliable tool for environmental data acquisition. The results support broader adoption of low-cost, IoT-based monitoring solutions that can complement institutional infrastructures and empower communities to engage in real-time environmental observation.

Table 2. BME280 Sensor Performance Summary after Calibration

Metric		Temperature	Humidity	Air Pressure
Accuracy		98.24%	98.37%	99.91%
Precision		99.13%	99.47%	99.01%
Bias		0.27 °C	0.74% RH	0.87 hPa

4 Conclusion

The linear calibration modelling of the BME280 sensor successfully enhanced the accuracy and reliability of environmental data acquisition. By integrating regression-based correction formulas into the NodeMCU ESP32 program, the system achieved high accuracy for temperature (98.24%), humidity (98.37%), and air pressure (99.91%). The calibrated sensor demonstrated excellent precision and low bias, confirming its suitability for IoT-based monitoring applications. This approach provides a practical framework for improving sensor performance in environmental monitoring systems, ensuring consistent and valid measurements for research and real-world applications.

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