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Utilization of Biomimetic Design on the Design of an Internet of Things-Based Smart Air Purifier in Urban Residences

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Abstract: Poor air quality in urban areas significantly impacts public health, productivity, and quality of life. Various efforts have been made to address this issue, but many solutions still have limitations, such as low effectiveness, designs that lack portability, and the inability for real time monitoring. This research aims to develop a smart air purifier based on biomimetics and the Internet of Things (IoT) as an innovative solution to improve air quality in urban residences. The device prototype mimics the mechanism of leaf stomata, which naturally regulate the flow of air and gases, thus enabling more optimal clean air circulation. The system can monitor environmental parameters, namely temperature, humidity, air pressure, and Indoor Air Quality (IAQ) Index, in real time using BME680 and MQ-135 sensors, and can be controlled via Google Assistant. Testing was conducted in three locations in West Java Province, Indonesia: Cilame, Cibiru, and Jatinangor. Linear regression analysis was used to evaluate the relationship between environmental variables and air quality. The results showed that the device was able to significantly improve air quality in all locations, especially in Cilame, with air pressure being the dominant factor affecting IAQ (coefficient of determination 0.88). Different from previous research, this device offers advantages in the form of high portability, real time monitoring, and IoT integration, making it a potential sustainable solution for improving the air quality of urban residences.

Keywords: *air quality; biomimetics; IoT; smart air purifier; urban*

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1. Introduction

Poor air quality has become an increasingly pressing global issue. Each year, air pollution is responsible for nearly seven million deaths worldwide [1]. In addition to outdoor (ambient) air pollution from industrial and transportation sectors, indoor air quality (IAQ) has also become a serious concern [2]. This is significant, as people spend approximately 40% of their daily lives indoors in homes, offices, schools, vehicles, and other public spaces where they are at risk of exposure to pollutants [3].

Indoor air is often contaminated by various pollutant sources, such as fine particulate matter (PM2.5), carbon dioxide (CO_2), volatile organic compounds (VOCs), cigarette smoke, and high humidity, which can promote mold growth [4][5]. Exposure to indoor air pollution negatively impacts health, leading to respiratory disorders, allergies, cardiovascular diseases, and even an increased risk of premature death [6][7]. Research shows that indoor air quality can be even worse than outdoor air, especially in urban areas with limited ventilation [8].

Previous studies have attempted to provide solutions through air filtration devices based on gas sensor technology. For example, Abbas et al. [9][10] developed a device using an Arduino Uno and an MQ-135 sensor to monitor indoor air pollution. However, their device had several limitations: its design was not portable, it could not specifically identify pollutant types, and it was not integrated with Internet of Things (IoT) technology for real time air quality monitoring [11]. Novelan [12] also designed a Bluetooth-based air quality monitoring system, but it had a limited signal range and lacked automatic device control features [13].

This research gap forms the basis of the present study. This research aims to develop a smart air purifier using a biomimetic approach, mimicking the mechanism of leaf stomata which naturally regulate air and gas flow, to help optimize the circulation of clean air indoors. The device is equipped with BME680 and MQ-135 sensors capable of monitoring environmental parameters including temperature, humidity, air pressure, and the Indoor Air Quality (IAQ) Index and is integrated with the IoT via Google Assistant for real time operation. It is hoped that this solution will serve as a more effective, portable, and adaptive innovation to address the air quality challenges in urban residences.

2. Method

The research was conducted from May to August 2024 in three locations within the Greater Bandung area, West Java Province: Jatinangor, Cibiru, and Cilame. These locations were selected based on criteria including high traffic congestion, dense population mobility, and varying levels of air pollution. Testing was carried out in a living room with an approximate area of 15 m², located in a standard residential house with natural ventilation to represent typical urban housing conditions. The primary focus of this research was to evaluate the device's ability to monitor indoor air quality parameters, including temperature, humidity, air pressure, and the Indoor Air Quality (IAQ) Index. Additionally, this study compared the air quality before and after the use of the device prototype.

2.1. Materials

This research utilized various components to build an Internet of Things (IoT) based air filtration system capable of monitoring air quality in real time and being controlled via Google Assistant. The MQ-135 gas sensor was used to detect harmful gases such as ammonia (NH_3) and carbon dioxide (CO_2) [14], while the BME680 sensor was used to measure temperature, humidity, air pressure, and volatile organic compounds (VOCs) that can affect air quality. The ESP32 module enabled IoT integration via Wi-Fi and Bluetooth [15], allowing the system to be automatically controlled through Google Assistant. Additionally, a humidifier module was used to increase air humidity, while an LCD display served to show the measurement data. All components were housed in a casing made from pine wood boards, selected for its natural properties that protect against mold and termites. The BME680 and MQ-135 sensors were used according to the manufacturer's specifications without recalibration, as both have built-in standard settings that were considered adequate for testing purposes under standard environmental conditions [16].

2.2. Research Procedure

Testing was conducted at three different locations: Jatinangor, Cibiru, and Cilame, each with varying environmental characteristics. The selection of these three locations was based on their high mobility levels and proximity to main roads, resulting in a greater potential for exposure to air pollution from vehicle traffic. This aligns with the research objective of evaluating the device's effectiveness under indoor air quality conditions influenced by urban activities.

The testing aimed to measure indoor air quality parameters, including temperature, humidity, air pressure, the Indoor Air Quality (IAQ) Index in units of µg/m³, and the concentration of air pollutants in parts per million (ppm). The BME680 sensor was used to measure temperature, humidity, air pressure, and volatile organic compounds (VOCs), while the MQ-135 sensor was used to detect the concentration of pollutant gases before and after the device was operated.

2.3.1 Temperature Measurement

Temperature was measured using the BME680 sensor, which is designed to monitor environmental conditions with a high degree of accuracy. This sensor was integrated with an ESP32 to read and record temperature data in real time. Measurements were taken at several points within the 15 m² living room.

2.3.2 Air Pressure Measurement

Air pressure was measured using the BME680 sensor at the point of highest activity within the room. This sensor is capable of accurately detecting changes in air pressure. The measurement process was conducted in accordance with the SNI 16-7052-2004 guidelines.

2.3.3 Indoor Air Quality *(IAQ) Measurement*

The Indoor Air Quality (IAQ) Index was measured using the MQ-135 sensor at the point of highest activity within the room. This sensor was used to detect air pollutant parameters such as carbon monoxide (CO), carbon dioxide (CO_2), ammonia (NH_3), and volatile organic compounds (VOCs). The measurement process referred to the SNI 9178:2023 guideline concerning "Ambient Air Quality Monitoring." The data obtained were used to calculate the Indoor Air Quality using the following equation:

$$AQI = \frac{C_i}{C_{max}} \times 100 \quad (1)$$

Where,

C_i : measured pollutant concentration (µg/m³ or ppm)

C_{max} : maximum concentration limit according to the SNI 9178:2023 standard

The calculated AQI results were then categorized based on the Air Pollutant Standard Index (ISPU) issued by the Ministry of Environment and Forestry (KLHK), as shown in **Table 1.**

Table 1. Air Pollutant Standard Index

NO	ISPU Range	Category
1	0-50	Good
2	51-100	Moderate
3	101-199	Unhealthy
4	200-299	Very Unhealthy
5	300-500	Hazardous

2.4. Data Analysis

The data obtained from measurements at the three research locations were analyzed to evaluate the relationship between environmental parameters and the Indoor Air Quality (IAQ) Index. The data analysis methods used included correlation analysis and linear regression analysis, which are described as follows:

2.4.1 Correlation Analysis

Correlation analysis was used to explore the relationship between the variables of temperature, humidity, and air pressure, and the IAQ value at each research location. The correlation coefficient value was calculated using the following equation:

$$r_{xy} = \frac{\sum(x_i - \bar{x})\,(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \cdot \sum(y_i - \bar{y})^2}} \tag{2}$$

Where,
x_i : value of the independent variable (temperature, humidity, or air pressure)
x_i : value of the dependent variable (IAQ)
$\bar{x}, \bar{y}$: the mean value of each respective variable

The results of the correlation analysis were visualized using a heatmap correlation matrix to facilitate the interpretation of relationship patterns between variables at each location. This visualization helps in identifying the environmental factors that have a significant influence on IAQ.

2.4.2 Linear Regression Analysis

Linear regression analysis was performed to evaluate the extent to which the variables of temperature, humidity, and air pressure could predict the IAQ value at each research location. The linear regression model was measured using the coefficient of determination ($\mathcal{R}^2$), which was calculated with the equation:

$$\mathcal{R}^2 = 1 - \frac{\mathcal{S}Sres}{\mathcal{S}Stot} \tag{3}$$

Where,
$\mathcal{S}Sres$: the residual sum of squares, which measures the difference between the actual IAQ values and the values predicted by the model.
$\mathcal{S}Stot$: the total sum of squares, which measures the total variation in the actual IAQ data.

The linear regression analysis aimed to identify which environmental variable contributed most significantly to the variation in IAQ values at each location. The regression results were then visualized through graphs that compared the actual IAQ values with the predicted values generated by the linear regression model.

3. Results and Discussion

An analysis was conducted to evaluate the distribution of the Indoor Air Quality (IAQ) and the factors influencing it at each research location. The three research locations have distinct environmental conditions. Jatinangor is a semi-urban area with numerous higher education institutions and moderate vegetation, but it is close to a busy national road; thus, although traffic pollution is present, air circulation is relatively better. Cibiru is a dense urban area with high commercial activity and traffic, as well as many tall buildings that can trap pollution, causing air quality to be stable yet vulnerable to vehicle emissions. Cilame is a suburban area near a light industrial zone and heavy traffic routes, contributing to greater pollution variability from industrial and vehicular activities. Its topography, enclosed by hills, can also affect air circulation. These differing conditions are factors that influence the distribution of IAQ values at each location.

3.1. Comparison of Indoor Air Quality *(IAQ) Across Locations*

A comparison of the Indoor Air Quality (IAQ) across locations was performed to identify variations in air quality distribution in Cilame, Cibiru, and Jatinangor. The analysis utilized a boxplot to visualize the distribution patterns, mean values, medians, and data variability at each site. The results of this analysis provide an understanding of the unique air quality dynamics in each region, as shown in **Figure 1.**

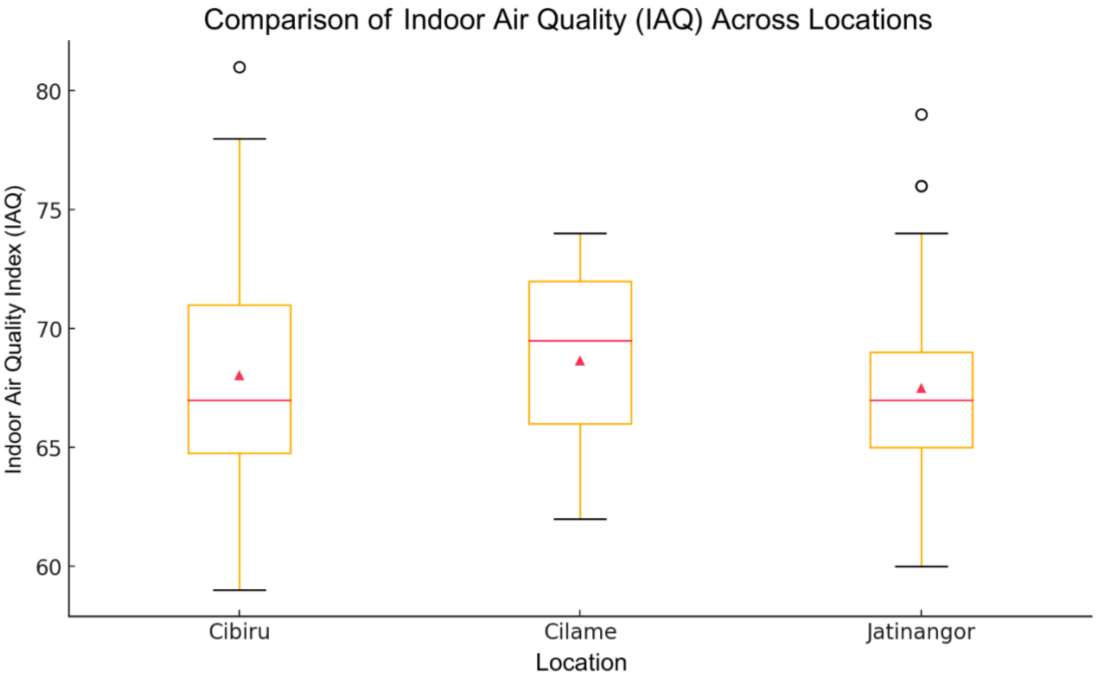


Figure 1. Comparison of the Indoor Air Quality (IAQ) across locations.

Figure 1 shows the comparison of the Indoor Air Quality (IAQ) at the three research locations Cibiru, Cilame, and Jatinangor visualized through a boxplot. This boxplot illustrates the data distribution range, mean, median, and outliers for each location.

Cibiru shows an IAQ distribution that is more centralized around the median, with several outliers at higher values. The interquartile range is relatively narrower compared to Cilame, indicating greater air quality stability at this location. Cilame has the widest IAQ value distribution range among the three locations. The median IAQ value here is higher than in Cibiru and Jatinangor, indicating greater air quality variation. The high deviation in IAQ values in Cilame is suspected to be caused by light industrial activity in the surrounding area and high traffic intensity during certain hours. Furthermore, Cilame's topography, which is surrounded by hills, may lead to less efficient air circulation, allowing pollutants to accumulate and cause high fluctuations in the IAQ value. Meanwhile, Jatinangor has a smaller IAQ value range with a distribution that tends to be stable, without many prominent outliers. This stability suggests that the air quality conditions in the Jatinangor area are more consistent than in the other two locations.

3.2. Correlation Analysis of Environmental Variables

To explore the relationship between environmental variables namely temperature, humidity, and air pressure and the Indoor Air Quality (IAQ) at each research location, a correlation analysis was performed and visualized using a heatmap [17]. This visualization provides a detailed overview of the relationship patterns among environmental variables at each location and helps identify factors that have a significant influence on IAQ, as shown in **Figure 2.**

Based on **Figure 2**, different relationship patterns among the variables were found at each research location. In Cilame, air pressure had a significant positive correlation with IAQ, suggesting that an increase in air pressure is correlated with better air quality. Conversely, temperature and humidity showed a negative correlation with IAQ, indicating that an increase in these two variables could degrade the air quality in this area. In Cibiru, humidity had the most significant correlation with IAQ, although the influence of air pressure on air quality was relatively smaller. The strong correlation between humidity and IAQ in Cibiru signifies that changes in humidity have a major impact on the air quality dynamics at this location.

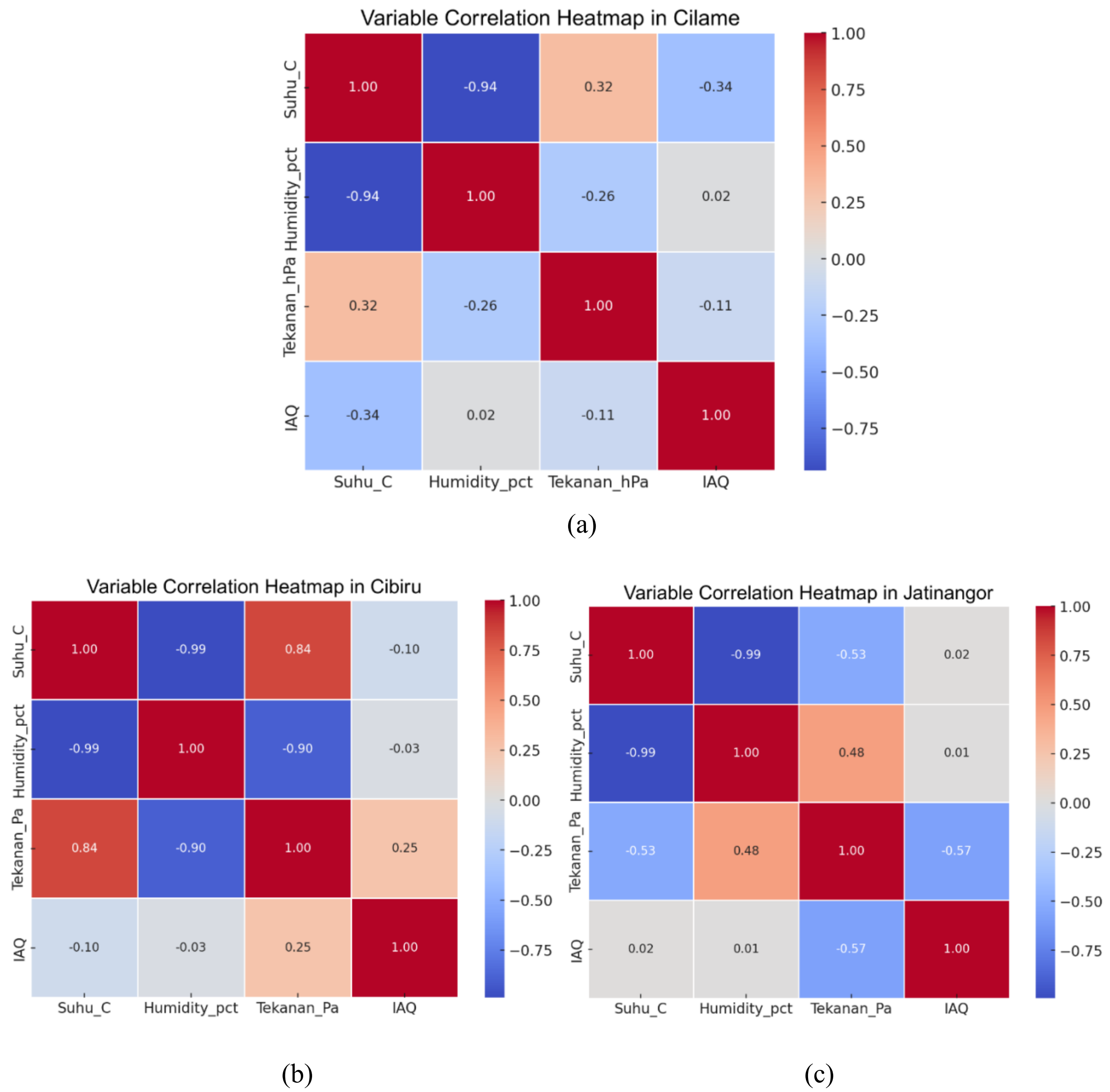
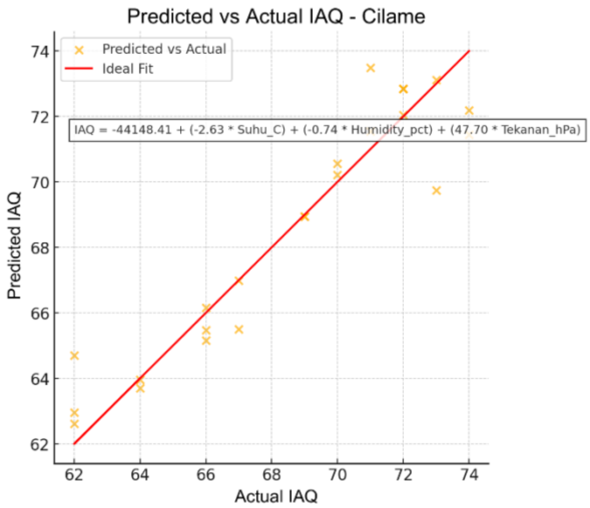


Figure 2. Correlation heatmap for the variables at (a) Cilame, (b) Cibiru, and (c) Jatinangor.

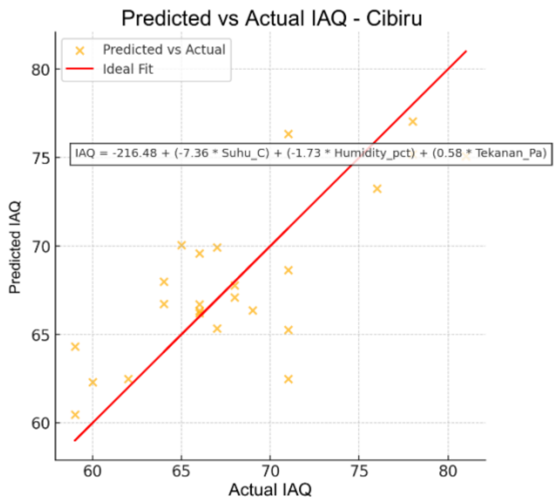
In Jatinangor, the relationship between all environmental variables and IAQ tended to be weaker compared to the other two locations. This suggests that unmeasured local factors, such as human activities or specific geographical characteristics, likely have a more dominant influence in determining air quality. Overall, this finding confirms the importance of considering local factors in the evaluation of air quality at each research location.

3.3. Linear Regression Test

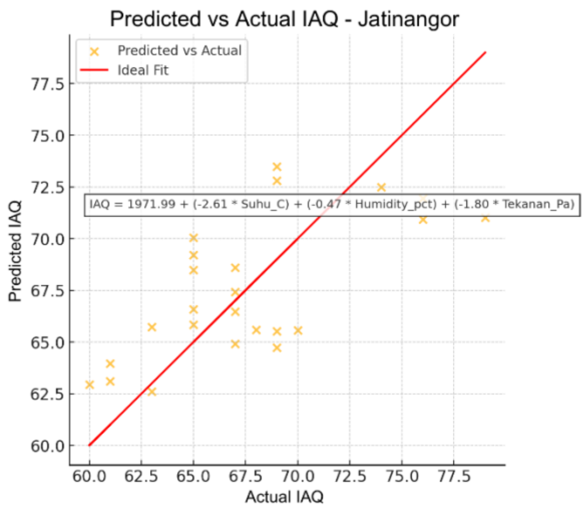
Linear regression analysis was used to evaluate the relationship between the environmental variables temperature, humidity, and air pressure and the Indoor Air Quality (IAQ) Index at each research location. The results of the regression analysis were visualized through graphs comparing the actual IAQ values with the predicted values generated by the model, as shown in **Figure 3.**



(a)



(b)



(c)

Figure 3. Comparison between actual and predicted Indoor Air Quality (IAQ) values for each location: (a) Cilame, (b) Cibiru, and (c) Jatinangor.

The analysis based on **Figure 3** shows the relationship between the actual and predicted IAQ values at the three research locations. In Jatinangor, the relationship between the actual and predicted IAQ values appeared weak, as indicated by a low $\mathcal{R}^2$ value. This indicates that the model was only able to explain a small portion of the IAQ variation, suggesting the possibility of other unmeasured external factors, such as human activities or specific geographical characteristics, having a more dominant influence in determining air quality. The data's considerable scatter around the ideal fit line reinforces this finding.

Conversely, in Cibiru, the regression model showed a stronger relationship between the environmental variables and IAQ. The higher $\mathcal{R}^2$ value indicates that the model could explain a majority of the variation in IAQ values, with temperature and humidity being the most influential variables compared to air pressure. Nevertheless, some deviations from the ideal prediction line were still present, possibly caused by additional unidentified variables or measurement uncertainties.

In Cilame, the regression model performed exceptionally well, with an $\mathcal{R}^2$ value approaching 0.88. This shows that the model was able to explain nearly all the variation in the IAQ values, with air pressure being the most significant variable. The data distribution in Cilame was observed to be very close to the ideal prediction line, indicating a high level of prediction accuracy and a consistent relationship between the environmental variables and IAQ at that location.

These research findings are in line with those of Zhou et al. (2020) [18], who also used an IoT-based gas sensor for indoor air quality monitoring and reported that temperature and humidity play crucial roles in Indoor Air Quality fluctuations. However, the present study is unique in its application of a biomimetic approach and the integration of Google Assistant for real-time operation, aspects that have not been widely explored in previous studies. Furthermore, the higher $\mathcal{R}^2$ value at the Cilame location indicates a better predictive performance of the model compared to similar studies that only achieved an average coefficient of determination below 0.75. This finding confirms the importance of considering local factors and specific environmental conditions in the development of IoT-based air quality monitoring systems.

4. Conclusion

This research aimed to examine the influence and application of biomimetics in an IoT-based smart air purifier for improving air quality in urban residences. To achieve this objective, a device prototype inspired by the mechanism of leaf stomata was developed, equipped with BME680 and MQ-135 sensors to monitor air quality parameters in real time. The system was supported by an ESP32 module for IoT integration via Google Assistant, enabling efficient operation. Testing was conducted in three locations with varying air pollution levels Cilame, Cibiru, and Jatinangor and the data were analyzed using linear regression to evaluate the relationships between environmental variables.

The research results demonstrate that the application of biomimetics significantly improved air quality at all test locations, particularly in Cilame, where air pressure was the dominant variable with a coefficient of determination of 0.88. Furthermore, the device exhibited high efficiency, portability, and adaptability to environmental changes. The novelty (findings) of this research lies in the integration of biomimetics with IoT technology, which offers an innovative and sustainable solution to address the challenges of urban air quality, while also making a tangible contribution to creating healthier and more comfortable living environments.

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