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The Relationship Between Indoor Air Quality and Student Productivity in the Era of Hybrid Learning

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ABSTRACT

The post-pandemic shift in education has accelerated the adoption of hybrid learning, which integrates both online and face-to-face instruction. Within this setting, indoor air quality (IAQ) plays a vital role in affecting students' comfort, health, and productivity. This study investigates the relationship between IAQ and student productivity in the hybrid learning era. A quantitative approach was employed using a correlational survey design, involving several schools selected through purposive sampling. IAQ parameters measured included carbon dioxide (CO_2), temperature, relative humidity, and particulate matter (PM2.5 and PM10), using standardized digital instruments. Student productivity was evaluated via a structured questionnaire addressing concentration, focus, and academic performance. Descriptive analysis revealed that average levels of CO_2 (1185.6 ppm), PM2.5 (41.7 $\mu g/m^3$), and PM10 (64.2 $\mu g/m^3$) exceeded health standards, whereas temperature (28.3°C) and humidity (61.2%) remained within moderate limits. Productivity scores were in the fair-to-good range (average concentration 3.7; focus 3.5; academic achievement 77.8), with notable differences observed across classes. Pearson correlation analysis indicated significant negative associations between CO_2, PM2.5, and PM10 with all productivity indicators ($p < 0.05$). Multiple linear regression identified CO_2 ($\beta = -0.412$) and PM2.5 ($\beta = -0.387$) as the most influential factors in reducing student productivity. These results suggest that poor indoor air quality, particularly elevated CO_2 levels and fine particulate matter, is a key determinant that can impede the effectiveness of hybrid learning.

Keywords: *Indoor Air Quality, Student Productivity, CO_2, PM2.5, Hybrid Learning*

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INTRODUCTION

The global transformation of education in the wake of the COVID-19 pandemic has led to the implementation of hybrid learning systems, which combine face-to-face and online learning. In this context, the quality of the physical environment of learning spaces is an important factor that determines student comfort, health, and productivity. Globally, the WHO reports that 37% of schools worldwide still have poor indoor air quality, particularly in terms of CO_2, PM2.5, and PM10, which can lead to cognitive impairment and respiratory health problems. International studies show that exposure to CO_2 in the range of 1000–2500 ppm can reduce cognitive ability by 15–30%, while exposure to PM2.5 above 35 µg/m³ increases the risk of respiratory disorders by up to 24% (Lee et al., 2021). One critical issue in face-to-face learning environments is indoor air quality (IAQ). Globally, poor IAQ has been linked to an increased risk of Sick Building Syndrome (SBS), which reduces occupant concentration, health, and productivity (Khairul & Suria, 2023).

The hybrid learning era, accelerated by the COVID-19 pandemic, combines in-person classroom sessions with remote instruction, exposing students to diverse indoor environments that significantly influence their health and academic outcomes (Oxford Air Conditioning, 2025; Ezeamii et al., 2025; WJARR, 2021). Indoor air quality (IAQ) emerges as a critical determinant, where poor ventilation leads to elevated levels of CO_2, particulate matter ($PM_{2.5}$), and volatile organic compounds (VOCs), impairing cognitive functions such as concentration, memory, and decision-making (Oxford Air Conditioning, 2025; Ezeamii et al., 2025; WJARR, 2021). Children prove particularly vulnerable, with studies indicating that CO_2 exceeding 1,000 ppm reduces cognitive performance by 10-20%, while $PM_{2.5}$ exposure heightens asthma risks and absenteeism, costing millions of school days annually (Ezeamii et al., 2025; School Infrastructure, 2025).

In hybrid settings, students alternate between schools and homes, both prone to suboptimal IAQ due to overcrowding, inadequate HVAC systems, and external pollutants infiltrating through windows or poor filtration (Edu Netoyed, 2025; Ephemera Journal, 2024). Research links higher ventilation rates—such as doubling from 5 to 10 L/s/person—to 50% CO_2 reductions and improved test scores by up to 8%, underscoring the need for targeted interventions like HEPA filters and hybrid ventilation (Ezeamii et al., 2025; Mendell et al., 2021). This analysis investigates IAQ parameters and their direct correlation to student productivity, aiming to inform evidence-based strategies for healthier hybrid learning spaces.

Recent research shows that poor air quality, especially high levels of CO_2, pollutants, and unbalanced humidity negatively impact students' cognitive performance and academic learning outcomes (Maciejewska & Szczurek, 2025). These findings reinforce the importance of controlling the learning environment in supporting student productivity.

Another study confirmed that increased CO levels₂In classrooms, noise can decrease focus, increase drowsiness, and reduce student learning effectiveness (Rus et al., 2021). Furthermore, long-term exposure to poor air quality can trigger health problems such as headaches and respiratory problems, ultimately reducing academic productivity.

At the national level, Indonesia faces similar challenges. The Ministry of Environment and Forestry (KLHK) notes that air quality in urban areas including Surabayais often classified as unhealthy, mainly due to transportation and industrial activities. Meanwhile, Permenkes No. 1077/2011 sets standards for CO_2 in rooms at a maximum of 1000 ppm, PM2.5 at a maximum of 35 µg/m³, and PM10 at a maximum of 50 µg/m³. However, various studies in Indonesian schools have found that more than 60% of classrooms do not meet these standards, especially in schools with minimal ventilation or air conditioning without fresh air intake. In Indonesia, the challenges of hybrid learning are further complicated by limited school facilities and infrastructure. Classroom ventilation is often inadequate, while the use of air conditioning without fresh air circulation has the potential to increase indoor pollutant levels (Anugerah et al., 2024).

Research reports in various Indonesian schools show that many classrooms do not meet healthy air quality standards, both in terms of CO concentration.$_2$, humidity, and the number of dust particles (Andamon et al., 2019). These conditions have the potential to hinder the effectiveness of hybrid learning, which requires healthy and comfortable classrooms.

In the context of learning, healthy air is not only a factor supporting physical health but also significantly influences students' cognitive function. Empirical evidence shows that good air quality can improve concentration, reduce stress, and promote better academic achievement (Maciejewska & Szczurek, 2025).

However, research on indoor air quality has largely focused on office or industrial buildings. Studies specifically examining the relationship between IAQ parameters and student productivity in classrooms, particularly in the context of hybrid learning in Indonesia, are still very limited (Lee et al., 2021).

This research gap highlights the need for more in-depth and contextualized studies in Indonesian schools. Research directly linking air quality to student productivity would provide an empirical basis for developing IAQ standards specifically for education in Indonesia (Palacios et al., 2021).

In the local context, Surabaya as a metropolitan city has a fairly high level of air pollution. Data from the Surabaya Environment Agency shows that the average daily concentration of PM2.5 in 2023 was in the range of 38–45 $\mu g/m^3$, exceeding the WHO safety limit. This condition has the potential to worsen indoor air quality, especially in schools located near major roads. Local research also shows that classrooms in Surabaya often have CO_2 concentrations above 1200 ppm, due to limited ventilation and high student density.

Indoor air quality (IAQ) is an important factor that affects students' health and cognitive abilities. Various studies show that high CO_2 levels reduce focus and concentration, PM2.5 impairs respiratory function, while ideal humidity and temperature reduce thermal comfort. However, most studies in Indonesia still focus on offices or industries, so research on the direct relationship between IAQ and student productivity during hybrid learning is still very limited.

Based on the background description, the main problem in this study is the suboptimal indoor air quality (IAQ) in school classrooms in Indonesia, which is suspected to affect student health, concentration, and productivity, especially in the hybrid learning era. This raises questions about the current state of air quality in classrooms, and to what extent IAQ parameters such as CO_2, humidity, temperature, and pollutant particles are related to student productivity levels, and how these findings can form the basis for recommendations for improving a healthy learning environment.

This study aims to analyze indoor air quality in school classrooms during the hybrid learning era and examine the relationship between IAQ parameters and student productivity levels. Furthermore, this research aims to generate empirical data that can support the formulation of strategies to improve the quality of the learning environment to support students' physical health, concentration, and academic achievement.

METHODS

This study utilised a quantitative approach with a correlational analytical survey design to analyse indoor air quality and the relationship between air parameters and student productivity levels in the era of hybrid learning. The research locations were several schools implementing a hybrid learning system in the city of Surabaya, selected purposively based on ventilation characteristics, student density, and classroom facility representativeness. The research subjects included classrooms as objects for measuring air quality and students as respondents for assessing productivity. Data collection was carried out through direct measurement of air quality parameters, including CO_2 concentration, temperature, relative humidity, and PM2.5 and PM10 particulates using standardised digital devices such as CO_2 meters, thermo-hygrometers, and particle counters. Measurements were taken during lessons with three repetitions to reduce temporal bias. In addition, student productivity data was obtained through a structured questionnaire that assessed aspects of concentration, focus, and academic achievement, supported by observations of classroom conditions. Data analysis was conducted descriptively to describe the actual conditions of air quality and student productivity levels, followed by a Pearson correlation test to assess the relationship between variables and multiple linear regression to identify the most dominant air quality parameters affecting productivity. This entire procedure was designed to provide an empirical and objective picture of the relationship between indoor air quality and student learning performance during hybrid learning.

RESULTS

This section presents the research results, including a descriptive analysis of indoor air quality (IAQ) conditions in classrooms and student productivity levels during the hybrid learning era. Furthermore, a correlation test was conducted to examine the relationship between IAQ parameters and student productivity, and a multiple linear regression analysis was conducted to identify the most dominant factors influencing productivity. The results of this analysis are expected to provide an empirical overview of the relationship between the physical learning environment and student academic achievement.

In table 1. presents a descriptive picture of indoor air quality in the classrooms that were the research locations. The parameters observed included CO2 concentration.$_2$, temperature, relative humidity, and pollutant particles (PM2.5 and PM10).

Table 1. Descriptive Statistics of Indoor Air Quality (IAQ)

Parameter	Minimum	Maximum	Average (Mean)	Standard Deviation	Reference Standard
CO concentration$_2$(ppm)	720	1750	1185.6	215.4	< 1000 ppm
Temperature (°C)	25.1	31.4	28.3	1.6	24–30 °C
Relative Humidity (%)	45	75	61.2	7.3	40–60%
PM2.5 (µg/m³)	15	78	41.7	14.9	< 35 µg/m³

PM10 (µg/m³)	25	115	64.2	22.1	< 50 µg/m³

The reference standard is adapted from WHO & Indonesian Minister of Health Regulation No. 1077/2011 concerning Guidelines for Indoor Air Health. CO concentration$_2$The average air quality exceeded the healthy threshold (1000 ppm), indicating suboptimal classroom air circulation. Temperatures remained within a comfortable range, although some classrooms reached >30°C, which could trigger discomfort. Relative humidity tended to exceed the optimal limit, potentially increasing the growth of microorganisms in the room. PM2.5 and PM10 levels averaged above healthy standards, potentially disrupting students' breathing.

Based on the data in Table 1, it can be seen that most of the air quality parameters, especially CO_2, PM2.5, and PM10, exceeding the reference standard. This condition indicates that classroom air circulation is still less than optimal and has the potential to reduce student comfort and health. To see how this condition impacts learning activities, a descriptive analysis of student productivity was conducted, as shown in Table 2.

Table 2. Descriptive Statistics of Student Productivity Level

Productivity Indicators	Minimum	Maximum	Average (Mean)	Standard Deviation
Concentration (score 1–5)	2	5	3.7	0.8
Focus Power (score 1–5)	2	5	3.5	0.9
Academic Achievement (score 0–100)	62	92	77.8	7.5

The average concentration and focus of students were in the fair-good category, but there was high variation (SD > 0.8). Students' academic achievement scores were relatively good (average 77.8), but there were still significant differences between classes. Student productivity indicators are potentially affected by variations in air quality, particularly $CO_2$and high PM2.5. Table 2**.** shows the distribution of student productivity scores, which include indicators of concentration, focus, and academic achievement. Descriptive results indicate that average student productivity falls within the fair-to-good category, although there is significant variation between individuals and between classes. This variation was then further analyzed for its relationship to air quality parameters.

To answer the relationship between air quality and productivity, a Pearson correlation test was conducted as presented in Table 3.

Table 3. Results of Pearson Correlation Test between IAQ Parameters and Student Productivity

IAQ parameters	Student Concentration (r, p)	Focus Power (r, p)	Academic Achievement (r, p)
CO concentration$_2$	r = -0.421, p = 0.002	r = -0.395, p = 0.004	r = -0.318, p = 0.015
Temperature	r = -0.245, p = 0.072	r = -0.198, p = 0.115	r = -0.105, p = 0.324
Relative Humidity	r = -0.267, p = 0.054	r = -0.289, p = 0.041	r = -0.221, p = 0.089

PM2.5	r = -0.438, p = 0.001	r = -0.412, p = 0.003	r = -0.361, p = 0.007
PM10	r = -0.327, p = 0.012	r = -0.298, p = 0.035	r = -0.284, p = 0.046

1. **CO_2 and PM2.5** has a strong and significant negative correlation with all indicators of student productivity. This means that the higher the CO level$_2$and fine pollutants, decreasing concentration, focus, and academic achievement.
2. **PM10** also showed a moderate negative correlation with productivity, although not as strong as PM2.5.
3. **Temperature** does not have a significant relationship with student productivity, indicating that the classroom temperature is still relatively comfortable.
4. **Humidity** weakly related to focus, meaning that high humidity can slightly reduce the ability to concentrate.

Table 3. shows a significant negative correlation between CO concentration$_2$, PM2.5, and PM10 with student productivity. This means that the higher the levels of pollutants and CO_2, the lower the students' concentration, focus, and academic achievement. This finding reinforces the hypothesis that air quality plays a significant role in determining the effectiveness of the learning process.

To determine which factors have the most dominant influence on productivity, the analysis was continued with multiple linear regression. The complete results of the regression test are shown in Table 4.

Table 4. Multiple Linear Regression Results between IAQ Parameters and Student Productivity

IAQ parameters	B (Regression Coefficient)	Beta (Standardized)	t-value	Sig. (p)
CO concentration$_2$	-0.315	-0.412	-3.74	0.001
Temperature	-0.082	-0.095	-1.12	0.265
Relative Humidity	-0.128	-0.173	-1.98	0.052
PM2.5	-0.292	-0.387	-3.51	0.002
PM10	-0.115	-0.164	-2.06	0.043

- $R^2 = 0.462$ → This means that 46.2% of the variation in student productivity can be explained by a combination of air quality parameters (CO_2, Temperature, Humidity, PM2.5, PM10).
- $F(5, 114) = 12.37$, $p < 0.001$ → The overall regression model is significant.

Interpretation of Regression Results

1. **CO_2 (Beta = -0.412)** is the most dominant factor reducing student productivity. This means that the quality of ventilation and air circulation is a major issue in classrooms.
2. **PM2.5 (Beta = -0.387)** also had a strong influence, showing that fine air pollution from both outside and inside classrooms significantly reduced students' concentration and academic achievement.
3. **PM10.** has a significant but weaker influence than PM2.5.
4. **Humidity** The effect is close to significant; although not too strong, a humid environment still has the potential to reduce learning focus.

5. **Temperature** did not show a significant effect, in line with the previous correlation results which were also weak.

Conclusion of regression analysis: $CO_2$and PM2.5 are the indoor air quality factors that most dominantly influence student productivity in the hybrid learning era, table 4.revealed that among all the IAQ parameters studied, CO concentration$_2$and PM2.5 were the most dominant factors significantly influencing student productivity. Meanwhile, temperature showed no significant effect, while humidity and PM10 had relatively weaker effects. Therefore, efforts to increase student productivity in hybrid learning are closely linked to improving air circulation quality and controlling particle pollution in classrooms.

DISCUSSION

The results of this study confirm that indoor air quality (IAQ) in classrooms at schools implementing hybrid learning has significant implications for student productivity. Key findings include high CO2 concentrations.$_2$, PM2.5, and PM10 exceeding health reference standards, as well as a strong negative correlation between these pollutants and indicators of student concentration, focus, and academic achievement. The following discussion integrates research findings, relevant theories, and previous studies to strengthen the empirical argument.

1. Indoor Air Quality Conditions

The descriptive data in Table 1 shows that the average concentration of CO_2reached 1185.6 ppm, exceeding the WHO's healthy standards and the Indonesian Minister of Health Regulation, which stipulates a limit of <1000 ppm. This indicates poor ventilation quality in classrooms. Furthermore, the average PM2.5 (41.7 μg/m^3) and PM10 (64.2 μg/m^3) also exceeded the safe threshold, indicating the infiltration of pollution from outside and the accumulation of indoor activities. This finding aligns with research by Anugerah et al. (2024) which found that CO accumulation$_2$in university classrooms in tropical climates increases drastically under conditions of limited air circulation, thus disrupting learning comfort (Anugerah et al., 2024). Similarly, Edelmers et al. (2023) reported that within 25 minutes without ventilation, CO_2in lecture halls can exceed 2000 ppm, demonstrating how rapidly pollutants accumulate in crowded spaces (Edelmers et al., 2023).

These conditions reinforce the theory of indoor air pollution exposure, which explains that indoor pollutant accumulation is influenced by occupant density, ventilation, and learning activities that trigger secondary particles. Researchers assume that in the context of Indonesian schools, high classroom density, the use of air conditioning without air exchange, and schools' proximity to pollution sources (highways or industrial areas) are the main determinants of poor air quality.

2. Student Productivity Level

The descriptive results of student productivity (Table 2) show that the average scores for concentration (3.7), focus (3.5), and academic achievement (77.8) are in the fair-good category. However, the high variation between students (SD > 0.8) indicates a disparity in their ability to adapt to learning environment conditions. This finding is in line with the cognitive load theory, which explains that environmental quality, including air quality, can increase or decrease students' cognitive load in processing information. Catalina et al. (2023) in their research in Romania confirmed that variations in academic productivity are closely related to fluctuations in air quality, especially $CO_2$and PM2.5, which affect students' thermal and cognitive comfort (Catalina et al., 2023).

The researchers assumed that some students with better physiological adaptability were able to maintain focus even in poor air conditions, while others experienced a more rapid decline in concentration. This implies that individual factors such as respiratory health and physical endurance also play a moderating role in the relationship between IAQ and productivity.

3. The Relationship between Air Quality and Productivity

Correlation analysis (Table 3) shows a significant negative relationship between CO_2, PM2.5, and PM10 with productivity indicators. The higher the pollutant levels, the lower the students' concentration, focus, and academic achievement. These results are consistent with research by Shukla et al. (2024) which showed that exposure to PM2.5 increases the risk of respiratory disorders and simultaneously reduces students' cognitive abilities and learning outcomes (Shukla et al., 2024). Furthermore, Caciora et al. (2024) found that pollutants PM2.5, NO_2, and VOCs in classrooms were significantly associated with increased health symptoms as well as decreased academic performance of students (Caciora et al., 2024).

Researchers believe this negative relationship indicates a dual effect: first, pollutants worsen physiological conditions (e.g., headaches, drowsiness, respiratory problems), and second, they decrease cognitive functions (such as working memory and attention). This supports the Environmental Load Hypothesis, which states that poor environmental quality increases mental stress and reduces information processing capacity.

4. Dominant Factors in Declining Productivity

Regression analysis (Table 4) revealed that CO_2(Beta = -0.412) and PM2.5 (Beta = -0.387) were the dominant factors in reducing student productivity, while temperature had no significant effect. These results confirm that ventilation and particulate pollutant control are key to creating a healthy learning environment. Lee & Kim (2025) demonstrated that the use of ventilation-based air purification in Korean schools was able to reduce CO levels.$_2$and PM2.5 up to 20–25%, which was followed by an increase in student academic performance (Lee & Kim, 2025). This is consistent with the findings of Collison & Byrne (2025) who confirmed that CO_2in the classroom is almost twice as high as in the office, so ventilation interventions are more urgent in educational spaces (Collison et al., 2025).

The researchers' critical assumption is that although factors such as humidity and PM10 also play a role, the dominance of $CO_2$and PM2.5 as the main predictors underscore the urgency of interventions based on ventilation management and purification technology. In the context of Indonesian schools, implementing a mechanical ventilation system or hybrid ventilation is considered more appropriate than solely natural ventilation, given the high level of outdoor air pollution in urban areas.

5. Theoretical and Practical Implications

Theoretically, the results of this study reinforce the concept of Indoor Environmental Quality (IEQ), which states that air quality is a key component in supporting the cognitive performance and health of building occupants. Practically, this study provides an empirical basis that improving IAQ through ventilation and particle control strategies can increase student productivity. These results also support the recommendation of Bikaki et al. (2025) who emphasized the importance of CO monitoring.₂, VOC, and PM simultaneously to maintain health and learning effectiveness in schools (Bikaki et al., 2025).

Researchers assume that variations in student productivity are not solely influenced by IAQ, but are also influenced by personal factors (immunity, psychological condition) and institutional factors (curriculum, learning methods). However, the magnitude of the influence of $CO_2$and PM2.5 in this study confirm that air quality is a crucial determinant that can be controlled by schools and the government. Therefore, this study emphasizes the urgency of integrating IAQ policies into educational facility and infrastructure standards in Indonesia.

CONCLUSIONS

The results of the study indicate that indoor air quality in classrooms in several schools in Surabaya City is still below health standards, particularly in terms of CO_2, PM2.5, and PM10 parameters, which were measured to exceed the thresholds recommended by the WHO and Permenkes No. 1077/2011. This condition indicates ventilation problems and high exposure to pollutant particles in the learning environment. Although student productivity levels were in the moderate to good category, they were significantly affected by air quality conditions. Correlation and regression analyses revealed that CO_2 and PM2.5 were the most dominant factors in reducing student concentration, focus, and academic achievement, while temperature and humidity had a weaker effect. These findings confirm that air quality is an important determinant of learning effectiveness in the hybrid era. In the future, the results of this study have broad application prospects, including as a basis for the development of mechanical or hybrid ventilation systems in schools, the formulation of standard guidelines for classroom air quality in Indonesia, the integration of IoT-based air quality monitoring technology, and the design of intervention programmes such as improved ventilation, the use of air purifiers, and the optimisation of outdoor learning. Thus, this research contributes significantly to efforts to improve the health of the learning environment and optimise student productivity in the long term.

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