

Indoor Air Quality in Tacloban City Public Schools: Assessment of PM_{2.5}, PM₁₀, and CO₂ Levels and Infrastructure Design Implications

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Abstract

This study assessed indoor air quality (IAQ) in selected public school classrooms in Tacloban City, Philippines by measuring particulate matter (PM_{2.5} and PM₁₀) and carbon dioxide (CO₂) concentrations and examining their relationship with building profile, ventilation characteristics, and environmental exposure. A quantitative descriptive cross-sectional design was employed in three public schools with similar DepEd/DPWH standard classroom building designs but different proximity to road and traffic sources. One typical classroom per floor was monitored, where available, from 07:00 to 18:00 using calibrated Temtop M2000 air quality monitors placed indoors and outdoors. Data were analyzed using descriptive statistics, indoor-outdoor ratios, Kruskal-Wallis tests, estimated air-change rates based on CO₂ decay, and Spearman correlation analysis. Results showed that mean PM_{2.5} concentrations ranged from 7.76 to 10.43 ug/m³, remaining below the WHO 24-hour guideline of 15 ug/m³. Mean PM₁₀ concentrations ranged from 34.56 to 46.51 ug/m³, with short-term exceedances observed in several classrooms and one mean value slightly above the WHO guideline of 45 ug/m³. Mean CO₂ concentrations ranged from 431.91 to 617.85 ppm, indicating generally adequate ventilation, although minor short-term exceedances occurred in two classrooms. PM_{2.5} indoor-outdoor ratios below 1.0 indicated strong outdoor influence with indoor dilution, while some PM₁₀ ratios above 1.0 suggested indoor dust resuspension. Kruskal-Wallis tests showed no significant floor-level differences for PM_{2.5}, PM₁₀, or CO₂. Correlations between CO₂ and particulate matter were weak to moderate and non-significant. The findings indicate that naturally ventilated classrooms can maintain acceptable CO₂ and PM_{2.5} levels under observed conditions, but PM₁₀ variability requires attention to dust control, traffic-source exposure, ventilation pathways, and routine IAQ monitoring. Evidence-based policy and infrastructure recommendations are proposed to support healthier school environments in tropical urban settings.

Keywords: Indoor Air Quality; PM_{2.5}; PM₁₀; Carbon Dioxide; Public Schools; Natural Ventilation; Tacloban City

Research Highlights

- The study provides localized baseline evidence on PM_{2.5}, PM₁₀, and CO₂ in naturally ventilated public school classrooms in Tacloban City.
- Mean PM_{2.5} and CO₂ levels were generally within guideline or benchmark values, while PM₁₀ showed greater variability and repeated short-term exceedances.

- Indoor-outdoor ratios suggest outdoor influence for PM_{2.5} and both outdoor infiltration and indoor dust resuspension for PM₁₀.
- No significant pollutant differences were found across floor levels, indicating that classroom microenvironment and source conditions may be more influential than elevation alone.
- The findings support practical design and operational measures involving ventilation management, dust reduction, school-site planning, and periodic IAQ monitoring.

1. Introduction

Indoor air quality (IAQ) is a critical component of school environmental health because students and teachers spend extended hours in classrooms where pollutant concentrations are shaped by ventilation, occupancy, outdoor sources, and indoor activities. In naturally ventilated classrooms, air exchange depends on wind, temperature differences, opening configuration, and building orientation. These conditions may reduce pollutant accumulation when airflow is favorable, but they may also allow outdoor traffic-related particles to enter indoor spaces when classrooms face roads or dense activity corridors (ASHRAE, 2019; Ren et al., 2020; Villanueva et al., 2021).

Particulate matter and carbon dioxide are among the most commonly used IAQ indicators in classrooms. PM_{2.5} can penetrate deeply into the respiratory system and has been associated with respiratory, cardiovascular, and cognitive risks, while PM₁₀ is linked with dust exposure, upper-airway irritation, and resuspension from indoor movement and cleaning practices (Oliveira et al., 2019; Sadrizadeh et al., 2022). CO₂ is generally interpreted as a ventilation and occupancy indicator. Elevated classroom CO₂ may indicate inadequate outdoor air supply and has been linked with reduced attention and cognitive performance in learning environments (Villanueva et al., 2021; Wargocki et al., 2020).

The Philippine context requires localized IAQ evidence because many public school classrooms use standardized building designs, rely heavily on natural ventilation, and are often located near roadways, transport routes, or densely built communities. Although standard classroom designs promote uniform construction, they do not guarantee uniform IAQ performance. Pollutant levels may vary according to classroom orientation, window placement, floor level, road proximity, surrounding land use, and operational practices such as window opening, fan use, cleaning, and classroom movement.

Tacloban City is a relevant setting for school IAQ assessment because it combines tropical humidity, coastal wind variability, post-disaster school infrastructure development, and public schools situated near traffic and community activity areas. After Super Typhoon Yolanda, many school facilities were reconstructed or repaired under standardized building approaches. However, the extent to which these structures support healthy IAQ under real operating conditions remains insufficiently documented. This study addresses that gap by assessing PM_{2.5}, PM₁₀, and CO₂ levels in selected Tacloban City public school classrooms and translating the findings into infrastructure and policy implications.

1.1 Aim and Objectives

This study aimed to assess indoor air quality in Tacloban City public schools and develop evidence-based policy recommendations for improving public school building design and IAQ management. Specifically, it sought to determine the typical building profile of selected school buildings in terms of building type, room dimensions, ventilation characteristics, orientation, and proximity to pollution sources; quantify IAQ in terms of PM_{2.5}, PM₁₀,

and CO₂; analyze the relationship between building profile and IAQ indicators; and formulate policy recommendations for public school buildings.

1.2 Theoretical and Conceptual Framework

The study was anchored on the IAQ conceptual model, natural ventilation theory, and the building envelope and air infiltration concept. The IAQ conceptual model explains that indoor pollutant concentrations result from the interaction of indoor sources, outdoor infiltration, ventilation, dilution, and removal mechanisms. Natural ventilation theory explains airflow movement through openings driven by wind forces and thermal differences. The building envelope concept explains how walls, windows, doors, roofs, and leakage paths regulate the exchange of air and pollutants between outdoor and indoor environments (ASHRAE, 2019; Gao & Niu, 2017; Morawska et al., 2017; World Health Organization, 2021).

In the present study, building and site profile variables were treated as explanatory conditions, while PM_{2.5}, PM₁₀, and CO₂ were measured outcome indicators. Association analysis examined indoor-outdoor pollutant behavior, floor-level variations, ventilation-related patterns, and correlation between CO₂ and particulate matter. The evidence-based output was a set of design and policy recommendations for improving indoor air quality in naturally ventilated public school classrooms.

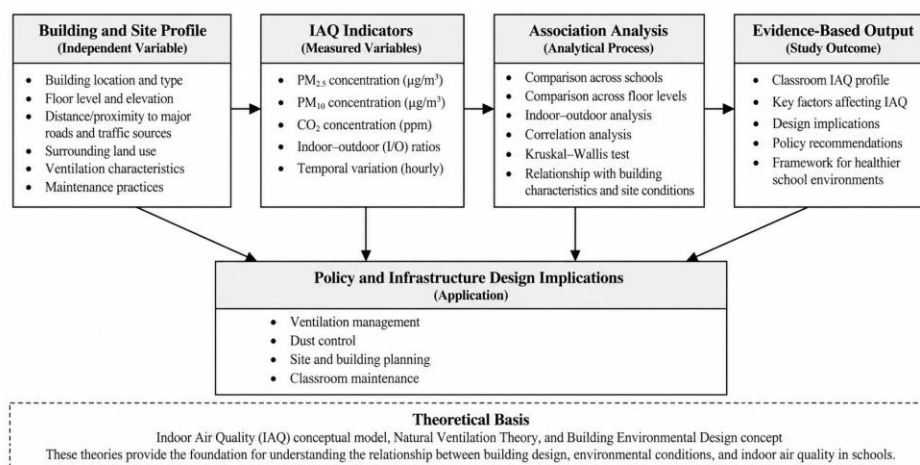


Figure 1. Conceptual Framework for Assessing Indoor Air Quality in Tacloban City Public Schools

Figure 1 presents the conceptual framework for assessing indoor air quality in Tacloban City public schools. It shows the logical flow of the study from classroom conditions and air quality measurements to analysis, findings, and policy implications.

The first component is the Building and Site Profile, which serves as the independent variable. It includes the physical and environmental characteristics of the selected school buildings, such as building location and type, floor level, proximity to major roads and traffic sources, surrounding land use, ventilation characteristics, and maintenance practices. These factors are important because they may influence how outdoor pollutants enter classrooms and how indoor air moves within the learning space.

The second component is the IAQ Indicators, which represent the measured variables of the study. These include PM_{2.5} concentration, PM₁₀ concentration, CO₂ concentration, indoor-outdoor ratios, and hourly temporal variation. PM_{2.5} and PM₁₀ indicate particulate pollution, while CO₂ is used as an indicator of ventilation adequacy.

The indoor–outdoor ratio helps determine whether pollutant levels are mainly influenced by outdoor infiltration or indoor sources such as dust resuspension and classroom activity.

The third component is the Association Analysis, which explains how the data were examined. The study compared air quality conditions across schools and floor levels, analyzed indoor–outdoor relationships, examined correlations among variables, and applied the Kruskal–Wallis test to determine whether pollutant concentrations differed significantly by floor level. This analytical stage links the building and site conditions with the measured IAQ indicators.

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The fourth component is the Evidence-Based Output, which refers to the study outcomes. These include the classroom IAQ profile, key factors affecting indoor air quality, design implications, policy recommendations, and a framework for healthier school environments. This output shows that the findings are intended not only to describe air quality conditions but also to guide practical school planning and infrastructure decisions.

The lower box, Policy and Infrastructure Design Implications, represents the applied contribution of the study. The arrows from the four upper components show that policy and design implications are drawn from the combined evidence on building profile, IAQ measurements, statistical analysis, and study outcomes. These implications focus on ventilation management, dust control, site and building planning, classroom maintenance, and periodic IAQ monitoring.

Figure 1 shows that indoor air quality in public school classrooms is shaped by the interaction of building design, site exposure, ventilation, pollutant behavior, and maintenance practices. The framework is anchored on the Indoor Air Quality conceptual model, Natural Ventilation Theory, and the Building Envelope/Infiltration concept, which explain how pollutants move between outdoor and indoor environments and how building features affect ventilation and exposure.

2. Literature Review

Current literature treats school IAQ as a combined environmental, public health, and infrastructure issue. Schoolchildren are vulnerable to particulate exposure because of their developing respiratory systems and high time spent in classrooms. Fine and coarse particles may originate from traffic, road dust, cleaning, chalk use, movement, and resuspension. Reviews of school environments consistently show that PM_{2.5} and PM₁₀ are linked with respiratory symptoms, discomfort, absenteeism, and potential cognitive effects, particularly in classrooms near roads or other external pollutant sources (Kalisa et al., 2023; Oliveira et al., 2019; Sadrizadeh et al., 2022).

Outdoor sources play a strong role in classroom exposure, especially in naturally ventilated schools. Studies of schools located near busy roadways show higher indoor traffic-related PM_{2.5}, black carbon, and nitrogen dioxide, indicating that road proximity and land-use context shape the exposure experienced by children (Matthaips et al., 2024; Osborne et al., 2021). In Philippine urban transport contexts, public utility vehicles and tricycles may contribute to roadside particle concentrations, making school siting and traffic exposure relevant to classroom IAQ (Madueño et al., 2019; Ruiz et al., 2025; Salison et al., 2025).

Ventilation is a central mechanism that can either reduce or increase exposure. Natural ventilation can dilute CO₂ and internally generated contaminants when outdoor air is relatively clean and airflow pathways are effective. However, opening windows facing traffic corridors can also increase indoor particle infiltration. Computational and field studies indicate that window placement, facade orientation, airflow distribution, wind direction, and surrounding obstructions influence pollutant transport in school buildings (Ren et al., 2020; Seng et al., 2024; Stabile et al., 2017; Trompetter et al., 2018).

CO₂ is used widely as a proxy for ventilation adequacy. Although CO₂ is not the only indicator of IAQ, it is useful in identifying occupied rooms with insufficient air exchange. Classroom studies have shown that high CO₂ concentrations may coincide with reduced cognitive performance, discomfort, and ventilation deficiencies (Villanueva et al., 2021; Wargocki et al., 2020). The 1,000 ppm threshold is commonly used as a practical ventilation benchmark and was used in the present study to interpret classroom ventilation adequacy.

The evidence also points to the need for calibrated low-cost monitoring in resource-constrained settings. Low-cost PM sensors are practical for school-based monitoring, but they may be affected by humidity, particle characteristics, and device-specific measurement bias. In high-humidity tropical settings, calibration and collocation with reference instruments are necessary to improve data reliability (Kosmopoulos et al., 2020; Wang et al., 2021; Zusman et al., 2020). This issue is particularly relevant in Tacloban City, where high relative humidity and coastal meteorology may influence both pollutant behavior and sensor performance.

Collectively, the literature supports localized IAQ assessment that integrates pollutant measurement, building characterization, site exposure, ventilation interpretation, and policy-oriented recommendations. The current study contributes to this body of evidence by examining standardized public school buildings in a tropical Philippine city and linking measured classroom IAQ with infrastructure design implications.

3. Methodology

3.1 Research Design

The study employed a quantitative descriptive cross-sectional research design. This design was appropriate for capturing classroom IAQ conditions during typical school operations and for comparing pollutant levels across selected schools and floor levels. The study focused on PM_{2.5}, PM₁₀, and CO₂ as the primary IAQ indicators. It did not collect individual health, academic performance, or personal exposure data; analyses were based on environmental measurements and observed classroom/building characteristics.

3.2 Research Environment and Sampling

The study was conducted in Tacloban City, Eastern Visayas, Philippines, a coastal and tropical urban center with public schools that commonly use standard classroom building designs. Three public schools were purposively selected based on the presence of multi-storey classroom buildings with similar or near-identical classroom layouts and varying proximity to major roads or jeepney routes. One typical classroom per available floor was monitored, resulting in nine classroom-floor monitoring locations.

Table 1. Target Schools

School Code	School Name
S01	Sagkahan National High School
S02	Leyte National High School
S03	Rizal Central School

Table 1 presents the three public schools selected as study sites for the indoor air quality assessment. Each school was assigned a code to maintain consistency in reporting: **S01** for Sagkahan National High School, **S02** for Leyte National High School, and **S03** for Rizal Central School. The table provides the basic identification of the monitored schools and serves as the reference for interpreting the succeeding results, including building profile, PM_{2.5}, PM₁₀, CO₂ levels, and school-level comparisons.

Table 2. Building Profile of Selected Classrooms

School	Floor	Building Type	Floor Area (m ²)	Room Dimensions (m)	Storeys	No. of Rooms
S01	F1	Reinforced concrete	60.63	8.85 x 6.85	4	3
S01	F2	Reinforced concrete	60.63	8.85 x 6.85	4	3
S01	F3	Reinforced concrete	60.63	8.85 x 6.85	4	3
S02	F1	Reinforced concrete	60.63	8.85 x 6.85	3	5
S02	F2	Reinforced concrete	60.63	8.85 x 6.85	3	5
S02	F3	Reinforced concrete	60.63	8.85 x 6.85	3	5
S03	F1	Reinforced concrete	60.63	8.85 x 6.85	4	2
S03	F2	Reinforced concrete	60.63	8.85 x 6.85	4	2
S03	F3	Reinforced concrete	60.63	8.85 x 6.85	4	2

Table 2 presents the physical profile of the selected classrooms used in the indoor air quality assessment. It shows that all monitored classrooms in S01, S02, and S03 were located in reinforced concrete buildings, indicating that the schools had similar structural characteristics.

The table also shows that the classrooms had the same floor area of 60.63 m² and the same room dimensions of 8.85 m × 6.85 m across all floors. This consistency is important because it allows the study to compare indoor air quality conditions across schools and floor levels with less variation caused by room size.

In terms of building height, S01 and S03 were located in four-storey buildings, while S02 was located in a three-storey building. The number of rooms also differed by school: S01 had 3 rooms, S02 had 5 rooms, and S03 had 2 rooms. These differences provide context for possible variations in ventilation, occupancy patterns, airflow, and pollutant movement.

Overall, Table 2 indicates that the selected classrooms had generally comparable room sizes and construction types, but differed in building height and number of rooms. These building characteristics are relevant in interpreting PM_{2.5}, PM₁₀, and CO₂ levels in the succeeding results.

3.3 Instrumentation and Validation

IAQ parameters were measured using two Temtop M2000 air quality monitors. One unit was used for indoor classroom monitoring and the other for simultaneous outdoor reference monitoring. The monitors measured

PM_{2.5}, PM₁₀, CO₂, temperature, and relative humidity. PM readings were based on optical sensing, while CO₂ readings were obtained using a non-dispersive infrared sensor. A handheld anemometer was used to obtain indicative airflow readings near windows, doors, and corridors, and a compass was used to document classroom facade orientation.

Before field deployment, the sensors underwent collocation and calibration at the DENR Continuous Ambient Air Quality Monitoring Station at Robinsons Tacloban City on 15 January 2026. The collocation analysis compared Temtop readings against the EMB reference instrument. The indoor-designated unit showed strong positive correlation for PM_{2.5} ($r = 0.830$) and moderate correlation for PM₁₀ ($r = 0.649$). Regression-based calibration equations were applied to reduce systematic bias prior to analysis.

3.4 Data Gathering Procedure

Monitoring was conducted during regular school hours from 07:00 to 18:00. Indoor and outdoor monitors were operated simultaneously to capture paired measurements. Indoor monitors were positioned in representative classroom locations, while outdoor monitors were placed at corresponding reference locations such as adjacent corridors or exterior areas. Field checklists documented occupancy, window and door status, fan use, classroom activities, weather notes, and other conditions that could influence IAQ. Measurements were used to compute descriptive statistics, exceedance counts, indoor-outdoor ratios, and ventilation-related indicators.

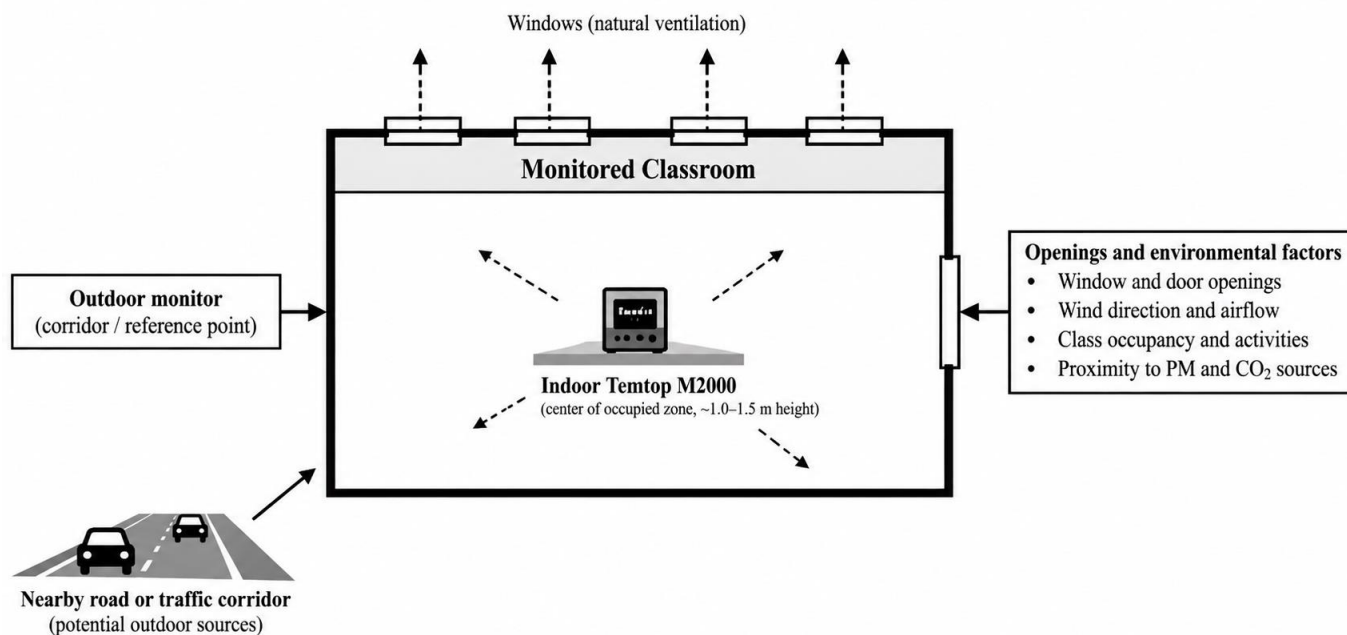


Figure 2. Schematic Diagram of the Monitoring Setup in the Classroom

Figure 2 shows the classroom monitoring setup used in the indoor air quality assessment. The indoor Temtop M2000 monitor was placed at the center of the occupied classroom zone, approximately 1.0–1.5 meters above the floor, to represent the breathing level of seated learners.

The figure also shows the outdoor monitor positioned at the corridor or reference point outside the classroom. This allowed simultaneous comparison of indoor and outdoor pollutant levels. The nearby road or traffic corridor is shown as a potential outdoor source of particulate matter that may enter the classroom through openings.

The windows and openings represent the natural ventilation pathway. Wind direction, airflow, class occupancy, classroom activities, and proximity to PM and CO₂ sources may influence the measured indoor air quality. Overall, the figure explains how the study captured classroom exposure by linking indoor monitoring, outdoor reference measurements, ventilation openings, and nearby pollution sources.

3.5 Data Analysis

Data analysis was quantitative. Descriptive statistics summarized pollutant means, maximum values, 95th percentiles, exceedance counts, and sample counts. WHO guideline values were used for PM_{2.5} and PM₁₀ interpretation, while 1,000 ppm was used as the classroom ventilation benchmark for CO₂. Indoor-outdoor ratios were computed by dividing indoor concentration by simultaneous outdoor concentration. Kruskal-Wallis tests were used to compare pollutant concentrations across floor levels because the study involved independent floor-level groups and non-parametric comparison was suitable for the monitoring data. Spearman correlation analysis examined relationships between CO₂ and particulate matter. Air-change rate was estimated from CO₂ decay during suitable periods using successive CO₂ readings.

3.6 Ethical Considerations

The study was conducted after securing permission from the concerned education authorities and school administrators. The research involved environmental measurements in classrooms and did not collect personal, medical, or academic performance data from students or teachers. Monitoring procedures were conducted with care to avoid disruption of classes. Data were reported at school and classroom-floor level without identifying individual occupants.

4. Results and Discussion

4.1 Indoor Air Quality Levels

The monitoring results showed generally acceptable PM_{2.5} and CO₂ levels in the selected classrooms, while PM₁₀ displayed more frequent short-term exceedances. Across the nine monitored classroom-floor locations, mean PM_{2.5} ranged from 7.76 to 10.43 ug/m³. These values were below the WHO 24-hour guideline of 15 ug/m³, although S01-F3 recorded two short-term exceedances. PM₁₀ ranged from 34.56 to 46.51 ug/m³, with S01-F3 slightly above the WHO 24-hour guideline of 45 ug/m³ and showing the highest number of exceedances. CO₂ ranged from 431.91 to 617.85 ppm, indicating generally adequate ventilation, with only minor short-term exceedances in S02-F1 and S03-F2.

Table 3. PM_{2.5} Summary Across Monitored Classrooms

School	Floor	Mean (ug/m ³)	Max	95th percentile	Exceedance >15	N
S01	F1	9.03	13.50	10.38	0	661
S01	F2	8.92	11.21	10.47	0	661
S01	F3	10.43	15.22	13.44	2	661
S02	F1	7.87	10.84	8.91	0	661
S02	F2	7.76	11.14	8.48	0	661
S02	F3	8.20	12.13	9.58	0	661
S03	F1	8.07	14.85	8.78	0	661
S03	F2	8.59	13.26	9.86	0	661
S03	F3	8.69	12.43	10.53	0	661

Note. WHO 24-hour guideline for PM_{2.5} = 15 ug/m³.

Table 3 summarizes the PM_{2.5} levels recorded across the monitored classrooms in the three selected public schools. It presents the mean, maximum value, 95th percentile, number of exceedances above the WHO guideline, and total number of observations per classroom.

The results show that the mean PM_{2.5} concentrations ranged from 7.76 to 10.43 µg/m³, which are all below the WHO 24-hour guideline of 15 µg/m³. This indicates that the average fine particulate matter levels in all monitored classrooms were within the acceptable reference limit.

The highest mean PM_{2.5} level was recorded in S01-F3 at 10.43 µg/m³, while the lowest was recorded in S02-F2 at 7.76 µg/m³. Only S01-F3 recorded exceedances above 15 µg/m³, with 2 instances out of 661 observations. This suggests that elevated PM_{2.5} levels were minimal and short-term.

Overall, Table 3 indicates that PM_{2.5} was not a major indoor air quality concern in the monitored classrooms during the study period. However, slight differences across schools and floors show that classroom location, airflow, and outdoor exposure may still influence fine particulate levels.

Table 4. PM₁₀ Summary Across Monitored Classrooms

School	Floor	Mean (ug/m ³)	Max	95th percentile	Exceedance >45	N
S01	F1	40.54	59.55	46.61	43	661
S01	F2	39.83	49.55	46.61	52	661
S01	F3	46.51	67.01	60.18	348	661
S02	F1	34.94	50.34	39.31	8	661
S02	F2	34.56	52.17	37.65	7	661
S02	F3	36.82	56.14	43.60	24	661
S03	F1	35.80	68.28	38.76	3	661
S03	F2	38.18	59.31	43.92	25	661
S03	F3	38.56	54.79	46.61	57	661

Note. WHO 24-hour guideline for PM₁₀ = 45 ug/m³.

Table 4 summarizes the PM₁₀ levels recorded across the monitored classrooms. It presents the mean concentration, maximum value, 95th percentile, exceedance count above the WHO guideline of 45 µg/m³, and the number of observations per classroom.

The results show that PM₁₀ levels were more critical than PM_{2.5}. Mean PM₁₀ concentrations ranged from 34.56 µg/m³ to 46.51 µg/m³. Most classrooms remained below the WHO guideline, but S01-F3 exceeded the limit with a mean of 46.51 µg/m³ and recorded the highest number of exceedances at 348 out of 661 observations.

The highest maximum PM₁₀ value was recorded in S03-F1 at 68.28 µg/m³, while several classrooms also showed elevated 95th percentile values. This indicates that PM₁₀ exceedances were not only isolated events but occurred repeatedly in some classrooms.

Table 4 suggests that PM₁₀ is the main particulate concern in the monitored classrooms. The elevated levels may be linked to outdoor dust, traffic-related particles, classroom movement, cleaning practices, and dust resuspension during school activities.

Table 5. CO₂ Summary Across Monitored Classrooms

School	Floor	Mean (ppm)	Max	95th percentile	Exceedance >1000	N
S01	F1	529.01	881	666	0	661
S01	F2	516.22	743	637	0	661
S01	F3	483.26	638	557	0	661
S02	F1	617.85	1045	735	2	661
S02	F2	584.28	909	759	0	661
S02	F3	547.14	981	687	0	661
S03	F1	475.46	592	525	0	661
S03	F2	434.83	1045	468	1	661
S03	F3	431.91	569	469	0	661

Note. CO₂ benchmark = 1,000 ppm.

Table 5 summarizes the CO₂ levels recorded across the monitored classrooms. It presents the mean, maximum value, 95th percentile, exceedance count above the 1,000 ppm benchmark, and total observations per classroom.

The results show that the mean CO₂ concentrations ranged from 431.91 ppm to 617.85 ppm, which are all below the 1,000 ppm benchmark. This indicates that the classrooms generally had adequate ventilation during the monitoring period.

The highest mean CO₂ level was recorded in S02-F1 at 617.85 ppm, while the lowest was recorded in S03-F3 at 431.91 ppm. Only two classrooms recorded short-term exceedances: S02-F1 had 2 exceedances, and S03-F2 had 1 exceedance. These exceedances were minimal compared with the total 661 observations per classroom.

Table 5 indicates that CO₂ was not a major concern in the monitored classrooms. Natural ventilation appeared sufficient to prevent sustained CO₂ accumulation. However, the occasional exceedances suggest that classroom occupancy, airflow, and window or door opening practices should still be monitored.

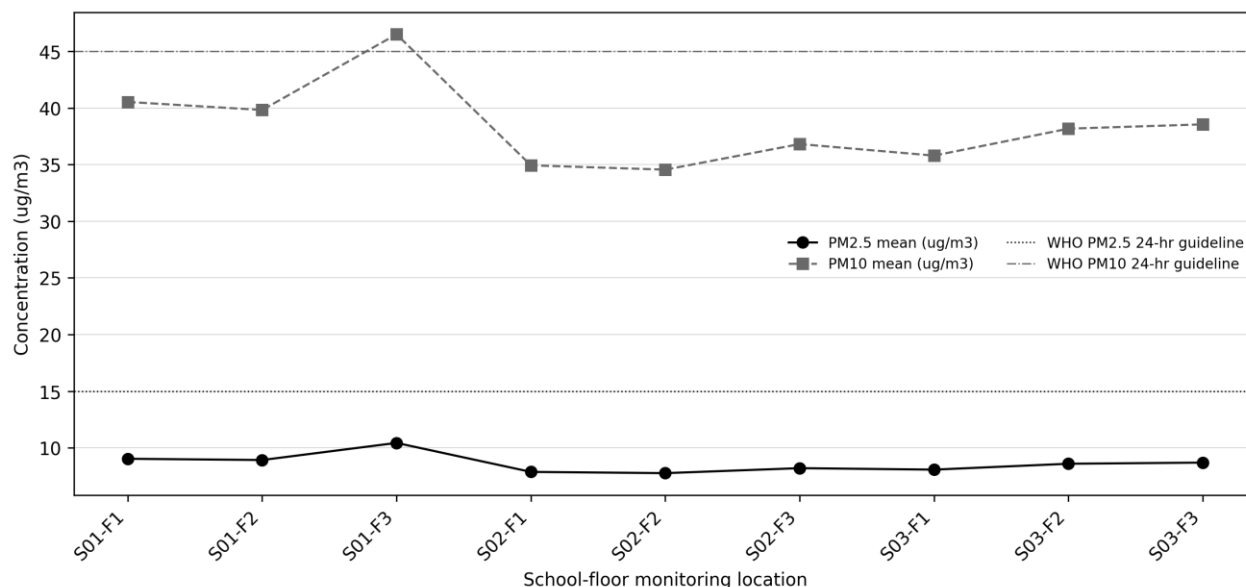


Figure 3. Mean PM_{2.5} and PM₁₀ concentrations across school-floor monitoring locations

Figure 3 presents the mean concentrations of PM_{2.5} and PM₁₀ across the school-floor monitoring locations. It compares the particulate matter levels recorded in each classroom by school code and floor level.

The figure shows that PM_{2.5} concentrations remained below the WHO 24-hour guideline of 15 $\mu\text{g}/\text{m}^3$ in all monitored classrooms. This means that fine particulate matter was generally within acceptable levels during the monitoring period.

In contrast, PM₁₀ concentrations were higher than PM_{2.5} across all school-floor locations. Several PM₁₀ values approached the WHO 24-hour guideline of 45 $\mu\text{g}/\text{m}^3$, while S01-F3 exceeded the guideline. This indicates that coarse particulate matter was the more critical air quality concern in the monitored classrooms.

The figure suggests that indoor air quality concerns were not mainly due to PM_{2.5} but were more related to PM₁₀, which may be influenced by outdoor dust, road-related particles, classroom movement, cleaning activities, and dust resuspension. The result supports the need for improved dust control, classroom maintenance, and ventilation management.

4.2 Compliance With IAQ Benchmarks

Comparison with benchmark values showed that PM_{2.5} levels were consistently within the WHO guideline based on mean and 95th percentile values. The highest PM_{2.5} maximum was 15.22 $\mu\text{g}/\text{m}^3$, indicating only a minimal short-term exceedance. In contrast, PM₁₀ showed repeated elevated levels. The maximum PM₁₀ concentration reached 68.28 $\mu\text{g}/\text{m}^3$, and the 95th percentile exceeded or approached the guideline in selected classrooms. These results suggest that coarse particle control is more urgent than fine particle control in the monitored classrooms. CO₂ results showed adequate ventilation overall. Mean values remained well below 1,000 ppm, and

95th percentile values were also below the benchmark, indicating no sustained CO₂ exceedance during the monitored school-day periods.

Table 6. Summary of PM_{2.5}, PM₁₀, and CO₂ Relative to Guideline Values

Indicator	Guideline / Benchmark	Observed Range	Interpretation
PM _{2.5} mean	15 ug/m ³	7.76-10.43 ug/m ³	Within guideline
PM _{2.5} maximum	15 ug/m ³	Up to 15.22 ug/m ³	Minimal short-term exceedance
PM ₁₀ mean	45 ug/m ³	34.56-46.51 ug/m ³	Near/at guideline
PM ₁₀ maximum	45 ug/m ³	Up to 68.28 ug/m ³	Exceeds guideline
CO ₂ mean	1,000 ppm	431.91-617.85 ppm	Within acceptable range
CO ₂ maximum	1,000 ppm	Up to 1,045 ppm	Short-term exceedance

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Table 6 summarizes the major indoor air quality indicators in relation to their guideline or benchmark values. It compares the observed ranges of PM_{2.5}, PM₁₀, and CO₂ with the WHO particulate matter guidelines and the 1,000 ppm CO₂ ventilation benchmark.

The table shows that PM_{2.5} mean values ranged from 7.76 to 10.43 µg/m³, which were below the guideline of 15 µg/m³. This indicates that fine particulate matter was generally within the acceptable level. However, the maximum PM_{2.5} value reached 15.22 µg/m³, showing only a minimal short-term exceedance.

For PM₁₀, the mean values ranged from 34.56 to 46.51 µg/m³. These values were near or slightly at the guideline of 45 µg/m³. The maximum PM₁₀ level reached 68.28 µg/m³, which exceeded the guideline. This suggests that PM₁₀ was the more critical air quality concern in the monitored classrooms.

For CO₂, the mean values ranged from 431.91 to 617.85 ppm, which were well below the 1,000 ppm benchmark. This indicates generally adequate ventilation. However, the maximum CO₂ value reached 1,045 ppm, showing a short-term exceedance.

Table 6 indicates that classroom ventilation was generally adequate, as shown by the low CO₂ levels. However, particulate matter, especially PM₁₀, still requires attention because it approached or exceeded guideline values in some instances. This supports the need for dust control, improved cleaning practices, and better management of airflow and outdoor pollutant entry.

4.3 Indoor-Outdoor Ratios and Source Interpretation

Indoor-outdoor ratios clarified possible source behavior. PM_{2.5} I/O ratios ranged from 0.825 to 0.869, all below 1.0, indicating that indoor PM_{2.5} was strongly influenced by outdoor conditions but diluted indoors under the monitored ventilation conditions. PM₁₀ I/O ratios were more variable. Several values exceeded 1.0, including S01-F1, S02-F1, S02-F2, S02-F3, and S03-F1, suggesting that indoor resuspension from movement, floor dust, cleaning practices, and classroom activity contributed to coarse particle levels. These findings support the interpretation that PM_{2.5} was more externally driven, whereas PM₁₀ reflected both outdoor infiltration and indoor activity-related sources.

Table 7. Indoor-Outdoor Ratios for PM_{2.5} and PM₁₀

School	Floor	PM _{2.5} I/O Ratio	PM ₁₀ I/O Ratio
S01	F1	0.869	1.023
S01	F2	0.825	0.935
S01	F3	0.866	0.926
S02	F1	0.835	1.060
S02	F2	0.844	1.091
S02	F3	0.859	1.074
S03	F1	0.839	1.042
S03	F2	0.828	0.973
S03	F3	0.835	0.980

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Table 7 presents the indoor–outdoor ratios for PM_{2.5} and PM₁₀ across the monitored classrooms. The I/O ratio shows whether particulate matter mainly came from outdoor sources or from indoor classroom activities. A value below 1.0 means indoor concentration was lower than outdoor concentration, while a value above 1.0 suggests possible indoor contribution.

For PM_{2.5}, all ratios ranged from 0.825 to 0.869, which are below 1.0. This indicates that fine particulate matter was mainly influenced by outdoor air infiltration, but indoor levels were slightly diluted inside the classrooms because of ventilation and particle settling.

For PM₁₀, the ratios were more variable, ranging from 0.926 to 1.091. Several classrooms recorded ratios above 1.0, especially S02-F1, S02-F2, S02-F3, and S03-F1. This suggests that coarse particulate matter was affected not only by outdoor dust and traffic-related particles but also by indoor sources, such as student movement, cleaning activities, floor dust, and resuspension of particles.

Table 7 shows that PM_{2.5} was mostly controlled by outdoor conditions, while PM₁₀ was influenced by both outdoor infiltration and indoor classroom activities. This supports the need for better dust control, damp cleaning, and proper ventilation management in classrooms.

4.4 Floor-Level Comparison and Ventilation Indicators

The Kruskal-Wallis test showed no statistically significant differences in PM_{2.5}, PM₁₀, or CO₂ concentrations across floor levels. This indicates that floor elevation alone did not explain pollutant variability in the monitored classrooms. Instead, local factors such as road exposure, indoor activity, ventilation pathway, airflow stagnation, and classroom operation likely played stronger roles. Estimated air-change rates ranged from 0.26 to 0.81 ACH in available CO₂ decay periods. These values indicate variability in ventilation behavior and suggest that the presence of windows and doors alone is not sufficient; airflow distribution and opening operation are also important.

Table 8. Kruskal-Wallis Test Results for Floor-Level Comparison of Pollutant Concentrations

Pollutant	H Statistic	p-value	Interpretation
PM _{2.5}	1.07	0.587	No significant difference
PM ₁₀	0.27	0.875	No significant difference
CO ₂	0.80	0.670	No significant difference

Table 8 presents the Kruskal–Wallis test results comparing pollutant concentrations across classroom floor levels. The test was used to determine whether PM_{2.5}, PM₁₀, and CO₂ levels differed significantly among floors.

The results show that all p-values were greater than the 0.05 level of significance: $PM_{2.5} = 0.587$, $PM_{10} = 0.875$, and $CO_2 = 0.670$. Therefore, there was no significant difference in pollutant concentrations across floor levels.

This means that whether a classroom was located on the first, second, or third floor did not significantly affect the measured indoor air quality. The findings suggest that other factors, such as ventilation conditions, classroom activity, outdoor dust, proximity to roads, and airflow pathways, may have stronger influence on pollutant levels than floor location alone.

Table 9. Estimated Air Change Rate Based on CO₂ Decay

School	Floor	C1 (ppm)	C2 (ppm)	Delta t (hours)	ACH
S01	F1	521	472	0.20	0.49
S01	F2	453	430	0.20	0.26
S01	F3	452	428	0.10	0.55
S02	F1	497	469	0.10	0.58
S02	F2	461	425	0.10	0.81
S02	F3	481	445	0.13	0.58
S03	F1	486	437	0.18	0.58

Table 9 presents the estimated air change rate based on CO₂ decay in the monitored classrooms. It shows how quickly indoor CO₂ levels decreased over a given time interval, which was used to estimate classroom ventilation performance.

The table shows that ACH values ranged from 0.26 to 0.81 among the reported classrooms. The highest estimated air change rate was recorded in S02-F2 with an ACH of 0.81, suggesting relatively better air exchange compared with the other rooms. The lowest value was recorded in S01-F2 with an ACH of 0.26, indicating weaker ventilation performance.

Most classrooms had ACH values around 0.49 to 0.58, which suggests moderate but variable natural ventilation. This means that air exchange was present, but its effectiveness differed depending on classroom conditions, opening configuration, airflow, and possible obstructions.

Table 9 indicates that the classrooms had some level of natural ventilation, which helped prevent sustained CO₂ buildup. However, the variation in ACH values shows that ventilation performance was not uniform across schools and floors. This supports the need to improve airflow distribution, reduce blocked openings, and consider better ventilation design in public school classrooms.

4.5 Correlation Between CO₂ and Particulate Matter

Spearman correlation analysis showed no significant relationship between CO₂ and PM_{2.5} or between CO₂ and PM₁₀. The CO₂-PM_{2.5} relationship was moderate negative but non-significant, while the CO₂-PM₁₀ relationship was weak negative and non-significant. This suggests that particulate levels were not driven primarily by occupancy-related ventilation conditions. Instead, PM concentrations were likely shaped by outdoor infiltration, dust resuspension, and activity-related coarse particle sources. The finding reinforces the need to interpret CO₂ and particulate matter as complementary but distinct IAQ indicators.

Table 10. Spearman Correlation Between CO₂ and Particulate Matter

Variable Pair	Spearman Correlation (rho)	p-value	Interpretation
CO ₂ vs PM _{2.5}	-0.45	0.224	Moderate negative, not significant
CO ₂ vs PM ₁₀	-0.30	0.433	Weak negative, not significant

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Table 10 presents the Spearman correlation results between CO₂ and particulate matter levels. It examines whether ventilation-related conditions, represented by CO₂, were significantly associated with PM_{2.5} and PM₁₀ concentrations.

The result for CO₂ and PM_{2.5} shows a moderate negative correlation, $\rho = -0.45$, but the relationship was not statistically significant because the p-value was 0.224, which is greater than 0.05. This means that although PM_{2.5} tended to decrease as CO₂ increased, the pattern was not strong enough to be considered statistically reliable.

The result for CO₂ and PM₁₀ shows a weak negative correlation, $\rho = -0.30$, with a p-value of 0.433. This also indicates no significant relationship.

Table 10 suggests that CO₂ and particulate matter were influenced by different factors. CO₂ mainly reflected classroom occupancy and ventilation, while PM_{2.5} and PM₁₀ were more likely affected by outdoor infiltration, dust, traffic-related particles, cleaning activities, and indoor resuspension. Therefore, adequate ventilation may reduce CO₂ levels, but it does not automatically reduce particulate matter levels.

5. Proposed Policy and Infrastructure Recommendations

The results support a school IAQ policy framework centered on ventilation, dust reduction, site planning, maintenance, and routine monitoring. First, school building orientation and ventilation openings should be planned to reduce direct exposure to nearby roads, dust-generating areas, and traffic corridors. Where feasible, classroom openings should be oriented away from major pollution sources, and setback distances should be considered during site planning. Second, airflow management should focus not only on the presence of windows and doors but also on actual airflow pathways, stagnant zones, and furniture arrangements that may block ventilation. Third, environmental control measures such as vegetation buffers, physical barriers, and dust-reducing landscaping should be considered, particularly for classrooms near roads. Fourth, housekeeping practices should minimize indoor PM₁₀ resuspension by using wet mopping or damp sweeping, scheduling cleaning outside occupied hours, and maintaining dust-free classroom surfaces. Finally, periodic PM_{2.5}, PM₁₀, and CO₂ monitoring should be institutionalized to provide evidence for classroom maintenance, ventilation improvement, and future infrastructure planning.

6. Conclusion

The study concluded that naturally ventilated public school classrooms in the selected Tacloban City schools generally maintained acceptable PM_{2.5} and CO₂ levels during the monitoring period, while PM₁₀ showed greater variability and repeated short-term exceedances. PM_{2.5} appeared to be strongly influenced by outdoor concentrations but diluted indoors, while PM₁₀ reflected both outdoor infiltration and indoor resuspension linked with classroom activities and dust. CO₂ levels suggested adequate ventilation, although airflow variability and estimated ACH values indicated that natural ventilation performance differed across classrooms. No significant

floor-level differences were found for the measured pollutants, and CO₂ was not significantly correlated with particulate matter. These findings demonstrate that acceptable CO₂ does not automatically mean that particulate exposure is fully controlled. IAQ management in public schools should therefore address both ventilation adequacy and particulate source control.

7. Recommendations

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It is recommended that DepEd, local government units, and school administrators integrate IAQ considerations into school infrastructure planning, classroom operation, and maintenance routines. Public schools should conduct periodic IAQ monitoring using calibrated instruments, prioritize PM₁₀ dust-control strategies, maintain effective natural ventilation where outdoor conditions permit, and improve site-level protection from traffic-related pollutants through buffers and setbacks. Future research should expand the number of schools, include wet-season and dry-season comparisons, monitor additional pollutants and biological contaminants, apply validated low-cost sensor calibration protocols, and use computational fluid dynamics or tracer methods to examine airflow pathways in standardized school buildings.

Declarations

Ethical Statement

The study involved classroom environmental monitoring and did not collect personal, medical, or academic data from students or teachers. Permission was secured from the concerned authorities and school administrators before field monitoring. Data were reported at classroom and school level to protect institutional and individual confidentiality.

Informed Consent

No individual participant intervention or personal data collection was conducted. Where classroom access and monitoring were required, institutional permission and site coordination were obtained before data collection.

Data Privacy and Confidentiality

The study used environmental monitoring data and classroom/building profile information. All data were handled for academic and research purposes only. No personally identifiable student or teacher information is reported in this manuscript.

Conflict of Interest

The author declares no conflict of interest in the conduct, analysis, interpretation, and publication of this study.

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Data Availability Statement

The data supporting the findings of this study may be made available from the author upon reasonable request, subject to institutional approval and applicable data privacy and school access requirements.

AI Usage Disclosure

Artificial intelligence assistance was used only for language refinement, formatting support, and manuscript organization. The author remains responsible for the content, analysis, interpretations, and final manuscript.

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