Techno-Science Research Journal V14 (1) (2026) P 24-31

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Techno-Science Research Journal

Journal Homepage: http://techno-srj.itc.edu.kh/

Techno-Science Research Journal

Assessing the Impact of Motorcycle Emissions on Urban Air Quality: A Case Study at the Institute of Technology of Cambodia

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Received: 11 June 2025; Revised: 26 August 2025; Accepted: 16 September 2025; Available online: April 2026

Abstract: *Air pollution is a growing environmental and public health concern in rapidly urbanizing cities such as Phnom Penh, Cambodia, where motorcycles account for over 80% of registered vehicles. Despite their dominance, localized data on motorcycle emission characteristics particularly under cold-start conditions remain limited, hindering evidence-based air quality management. This study quantifies particulate matter (PM) emissions from motorcycles during idle engine operation in a semi-enclosed university parking environment and examines the influence of fuel type, engine size, vehicle age, and model on emission levels. Field measurements were conducted on 150 motorcycles at the Institute of Technology of Cambodia, with 135 included in final analysis. PM concentrations (0.3–10.0 µm) were recorded using a ZJSJ-G portable laser particle counter over a three-minute idling cycle immediately after ignition. Descriptive statistics, Welch's t-tests, one-way ANOVA, and two-way ANOVA were employed to assess differences and interactions among categorical variables. Results show that PM concentrations peaked sharply during the first minute of idling (mean: 564.50 µg/m^3) before declining to 159.01 µg/m^3 by the third minute. Fuel type had the strongest influence: motorcycles using higher-grade Super gasoline emitted significantly less PM than those using Simple or mixed fuels ($p < 0.001$). Vehicle age also significantly affected emissions, with mid-aged motorcycles (4–7 years) producing the highest levels. Engine size was not a significant predictor, but model-specific differences were observed, suggesting the role of design and technology in emission performance. These findings highlight the cold-start phase as a major but under addressed source of urban PM pollution. Policy recommendations include upgrading fuel quality standards, implementing targeted inspections for mid-aged motorcycles, introducing model-specific emission benchmarks, and improving ventilation in high-density parking areas. The study provides the first localized evidence on motorcycle cold-start emissions in Cambodia, directly supporting the National Clean Air Plan (2022–2030) and offering actionable pathways to reduce PM emissions and protect public health in rapidly motorizing Southeast Asian cities.*

Keywords: Air pollution, Cold-Start Emissions, Motorcycle emissions, Particulate matter (PM), Sustainable urban mobility

1. INTRODUCTION

Air pollution is an escalating environmental and public health challenge in rapidly urbanizing cities such as Phnom Penh, Cambodia [1]. Among the primary contributors to this problem are emissions from motorized vehicles, particularly motorcycles, which dominate the urban transport system. In Phnom Penh, motorcycles represent over 80% of all registered vehicles, making them the most prevalent mode of transport [2]. Despite their dominance, the emission characteristics of motorcycles remain under-researched in Cambodia, creating a critical gap in the country's urban air quality management efforts [3].

Numerous studies across Southeast Asia have demonstrated the significant contribution of motorcycles to urban air pollution. In Bangkok, for example, two-wheelers have been shown to emit large quantities of fine particulate matter (PM2.5) and hydrocarbons, particularly when older or poorly maintained [4]. Similar patterns have been observed in Jakarta and Ho Chi Minh City, where outdated motorcycle fleets and the use of low-quality fuels contribute to elevated emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and PM [5,6,7]. Exposure to fine particulate matter has been linked to serious health risks. Brook et al.

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DOI : https://doi.org/10.64702/Techno-SRJ.2026.V14.I1.04
Published by Institute of Technology of Cambodia.

(2010) reported strong correlations between PM exposure and cardiovascular and respiratory diseases [8], while Ting et al. (2023) found increased respiratory symptoms among young adults frequently exposed to traffic-related pollution in school and university environments [9]. The “cold-start” phenomenon when engines emit higher pollutant levels immediately after ignition due to incomplete combustion is especially relevant in semi-enclosed motorcycle parking areas where frequent starting and stopping occurs [10,11]. National policy developments in Cambodia have recently begun to address these concerns. As of January 2022, all newly imported vehicles are required to meet Euro 4 emission standards, with Euro 5 compliance scheduled for 2027. Vehicle inspection centers have expanded nationwide to support enforcement, although motorcycles are not consistently included in routine emissions testing [12]. The country’s National Clean Air Plan (2022-2030) and updated Nationally Determined Contributions (NDCs) recognize the transportation sector as a major target for emission reduction, projecting that pollution from road traffic could double by 2030 if unaddressed [12,13].

Despite these policy developments, localized empirical data on motorcycle emissions especially under idle or cold-start conditions are still lacking in Cambodia’s urban academic environments. This gap hinders the formulation of evidence-based strategies tailored to local transport behaviors and pollution patterns. In parallel, electric motorcycles are increasingly promoted as a cleaner alternative, since they produce zero tailpipe emissions. However, their overall environmental benefits depend on lifecycle factors such as electricity generation, battery production, and disposal, which are beyond the scope of this study.

Therefore, this study aims to address the following three objectives: (1) Quantify PM emissions produced by motorcycles during idle engine conditions in a semi-enclosed campus parking environment using standardized measurement tools, (2) Assess statistically significant differences in PM emissions based on motorcycle characteristics specifically fuel type, engine size, vehicle age, and model using t-tests and ANOVA methods and (3) Generate evidence-based recommendations for emission reduction in academic settings by interpreting the statistical results in the context of local fuel policies and motorcycle usage patterns.

This research contributes localized, data-driven insight into motorcycle-related emissions and offers practical implications for transport emissions management in Southeast Asian cities. By focusing on motorcycles under cold-start conditions in a real-world urban microenvironment, the study supports more targeted and context-specific air quality policies.

2. METHODOLOGY

2.1 Study area

This study was conducted at the Institute of Technology of Cambodia (ITC), located along Russian Federation Boulevard in Phnom Penh. ITC is one of Cambodia’s leading engineering universities, accommodating over 10,000 students and staff, most of whom commute by motorcycle. The campus contains approximately 2,800 motorcycle parking spaces. The emission measurements were performed in designated semi-enclosed motorcycle parking areas with limited natural ventilation ideal conditions for assessing cold-start particulate matter (PM) emissions and their immediate environmental impact (Figure 1).

Fig 1. Study Area at Institute of Technology of Cambodia (ITC).

2.2 Study Design and Data Collection

A cross-sectional field study was employed, in which 150 motorcycles were measured on the ITC. From this group, 135 motorcycles were randomly selected for detailed analysis based on the completeness of information and consistency in testing conditions. Each motorcycle was measured over a three-minute idling cycle immediately after ignition, simulating cold-start operation. PM concentrations were recorded at Minute 1, Minute 2, and Minute 3 to capture both the cold-start phase and the transition to steady-state combustion. A ZJSJ-G portable laser particle counter was used to record particulate matter (PM) concentrations. This instrument detects particles in the size range of 0.3 to 10.0 µm with a sampling flow rate of 28.3 L/min. Emission sampling was conducted under a standardized semi-enclosed hood placed near the exhaust to ensure consistency and minimize ambient interference. The motorcycles were categorized by fuel type (Simple or Super gasoline), vehicle age group (0–3 years, 4–7 years, 8+ years), engine size

(100–110cc, 111–125cc, 126–150cc), and model types with different gear system (i.e., MC1-Automatic, MC2-Manual, MC3-Automatic, MC4-Automatic, MC5-Automatic, MC6-Manual, MC7-Automatic). Noted that brand names of these motorcycles are not exposed, as the brand name may not be the factor affecting level of air polluting emissions. Instrument calibration was verified through manufacturer settings prior to deployment. Daily zero-checks were performed using HEPA-filtered air to ensure sensor stability. While laboratory-grade calibration against reference particle concentrations was not conducted due to field constraints, the instrument performance was validated against benchmark values from previous regional studies.

All PM emission data were compiled and cleaned using Microsoft Excel. Descriptive statistics such as mean and standard deviation were calculated for each idling minute. Statistical analyses were conducted using Python. An independent samples t-test (specifically Welch's t-test) was used to compare first-minute emissions between motorcycles using Simple and Super gasoline, accounting for unequal group sizes and variance. One-way ANOVA was applied to test differences across motorcycle age groups, engine sizes, and model types. Where significant differences were found, Tukey's HSD post-hoc test was employed to identify which specific group pairs differed. In addition, a two-way ANOVA was conducted to assess the interaction between fuel type and motorcycle model. All statistical tests were carried out at a 95% confidence level ($\alpha = 0.05$), and appropriate adjustments were made where test assumptions were not fully met.

3. RESULTS

3.1 Descriptive Statistics

Table 1 provides an in-depth analysis of motorcycle features, including their manufacturing year, performance metrics over specific time intervals, age, engine size, and usage statistics. The average motorcycle age was 5.8 years (range: 0–16 years), reflecting a range of both newer and older models, produced between 2008 and 2024. Performance metrics measured over 1, 2, and 3 minutes reveal significant variability, with averages of 564.5 µg/m^3, 250.31 µg/m^3, and 159.01 µg/m^3, respectively, suggesting a decline in performance over time. Most motorcycles in the dataset had small to mid-sized engines: 100–110 cc (40%), 111–125 cc (45%), and 126–150 cc (15%). The overall average engine size was 117.3 cc. Furthermore, the average cumulative distance of 270428.38 indicates considerable variability in usage among the motorcycles in the dataset.

Table 1. Descriptive Statistics of Motorcycle Characteristics

Variable	Mean	SD	Min	Max
Year	2018.23	3.17	2008	2024
Minute 1 (µg/m^3)	564.50	765.98	53.18	7790.08
Minute 2 (µg/m^3)	250.31	396.97	46.77	4629.87
Minute 3 (µg/m^3)	159.01	130.31	36.91	1128.91
Age (years)	5.77	3.17	0	16
Engine Size	117.31	7.98	110	150
Odometer (km)	270428.4	212264.9	6445	918384

The graph illustrates a notable decrease in average PM concentration over three minutes, starting at about 564.5 µg/m^3 at minute 1, falling to around 250.31 µg/m^3 at minute 2, and reaching approximately 159.01 µg/m^3 by minute 3, reflecting a reduction in particulate matter levels over time. This significant decline in PM concentration suggests an effective mitigation of airborne pollutants during the observed timeframe. The initial level of 564.5 µg/m^3 indicates a critical pollution event, likely influenced by factors such as increased vehicular emissions. The rapid decrease to 250.31 µg/m^3 by the second minute is likely due to incomplete combustion during the cold-start phase. As the engine warms up, combustion efficiency improves, leading to a sharp reduction in particulate emissions. Similar patterns have been reported in enclosed parking and tunnel environments [11,9].

However, the rapid decrease to 250.31 µg/m^3 at the two-minute mark implies a potential intervention, whether through regulatory measures, improved filtration systems, or a reduction in local emissions.

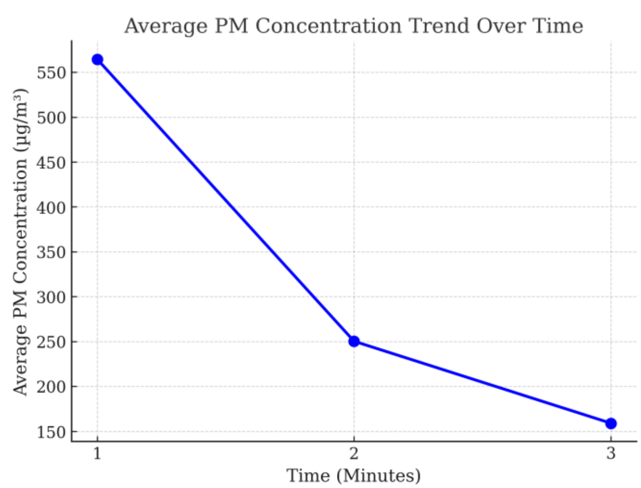

Fig 2. Trend of Average PM Concentration Over Time

By the end of the three minutes, the concentration stabilizing around 159.01 µg/m^3 indicates a successful response to the pollution point, showcasing the effectiveness of implemented strategies or natural dispersion mechanisms. This trend not only highlights the dynamic nature of air quality but also emphasizes the importance of continuous monitoring and timely action to protect public health. The data underscores the need for ongoing efforts to maintain and further improve air quality standards, ensuring a healthier environment for all.

Motorcycles with engines 110cc have the highest emissions at 1 minute, which significantly decrease by 2 and 3 minutes. Engines in the 111-125cc range also peak at 1 minute but show a notable weakening over time. In contrast, 126-150cc engines consistently produce the lowest emissions across all intervals. This trend suggests that smaller engines, particularly those 110cc, may be less efficient in their combustion processes, leading to higher emissions initially. As time progresses, the reduction in emissions for these smaller engines could indicate a gradual improvement in combustion efficiency or a decrease in fuel delivery as the engine warms up.

The decline in emissions after the first minute is more plausibly explained by incomplete combustion during cold-start conditions, which stabilizes as the engine warms up. This pattern was consistent across engine sizes, with larger engines (126-150cc) showing lower overall emissions, indicating that their design may incorporate better emission control technologies or more efficient combustion strategies from the outset, similar findings were reported in the National Clean Air Plan [12]. This consistent performance across all intervals suggests a more stable operational efficiency, which could be attributed to stricter regulatory standards or innovative engineering practices aimed at reducing environmental impact.

Table 2 shows the average particulate matter (PM) emissions from motorcycles based on their age categories. The results indicate that motorcycle age significantly influences emission levels at all measured time intervals. Motorcycles aged 0–3 years emit 465.37 $\mu g/m^3$ at Minute 1, which drops to 199.86 $\mu g/m^3$ at Minute 2 and further decreases to 154.83 $\mu g/m^3$ at Minute 3.

In contrast, motorcycles aged 4–7 years show the highest emissions across all intervals, beginning at 764.28 $\mu g/m^3$ at 1 minute, then reducing to 320.38 $\mu g/m^3$ and 226.25 $\mu g/m^3$ at 2 and 3 minutes, respectively. For motorcycles aged 8 years and above, the emissions start at 705.65 $\mu g/m^3$ at 1 minute, followed by 352.4 $\mu g/m^3$ at 2 minutes and 262.06 $\mu g/m^3$ at 3 minutes. These results suggest that newer motorcycles produce significantly lower emissions, while older motorcycles especially those aged 4 years and above emit considerably more PM, particularly during initial engine operation. This trend highlights the impact of vehicle aging on air pollution and the importance of emission control policies targeting older motorcycles.

The average PM emissions based on different gasoline types. Motorcycles using a combination of Simple/Super gasoline recorded the highest particulate matter emissions across all time intervals, beginning with 1514.00 $\mu g/m^3$ at Minute 1 (min 1) and decreasing to 375.03 $\mu g/m^3$ at Minute 3 (min 3). In comparison, motorcycles using Simple gasoline emitted 567.91 $\mu g/m^3$ initially, dropping to 151.78 $\mu g/m^3$ by the third minute. Super gasoline resulted in the lowest emissions at 1 minute (511.87 $\mu g/m^3$) but recorded slightly higher values at 3 minutes (181.08 $\mu g/m^3$) than Simple gasoline. Overall, emissions consistently declined over time for all fuel types, which may indicate increased combustion efficiency as engine temperature rises. However, the persistently high values from the Simple/Super fuel group suggest it may produce more pollutants, possibly due to inconsistent fuel quality or suboptimal combustion characteristics.

Table 2. Descriptive Statistics of PM Emissions ($\mu g/m^3$) by Engine Size, Age, Fuel Type, and Model (N=150)

Factor	Minute 1	Minute 2	Minute 3	Average
Engine Size Group				
110 cc	515.39	204.33	140.68	286.80
111-125 cc	623.64	303.58	180.27	369.16
126-150 cc	285.08	130.31	109.15	174.85
Age (Years)				
0–3 years	465.37	199.86	154.83	273.35
4–7 years	764.28	320.38	226.25	436.97
8+ years	705.65	352.40	262.06	440.04
Gasoline Type				
Simple	567.91	249.62	151.78	323.10
Simple/Super	1514.91	616.29	375.03	835.41
Super	511.87	242.39	181.08	311.78
Type of Motorcycle				
MC1-Automatic	406.95	152.59	97.91	219.35
MC2-Manual	559.50	250.53	181.20	330.41
MC3-Automatic	420.89	189.51	140.94	250.45
MC4-Automatic	388.17	207.12	121.20	238.83
MC5-Automatic	486.28	178.12	131.75	265.38
MC6-Manual	577.34	277.81	186.78	347.31
MC7-Automatic	503.45	200.95	133.76	279.39

Noted: MC1-Automatic refers to motorcycle type 1 with automatic gear system, MC2-Manual refers to motorcycle type 2 with manual gear system, MC3-Automatic refers to motorcycle type 3 with automatic gear system, MC4-Automatic refers to motorcycle type 4 with automatic gear system, MC5-Automatic refers to motorcycle type 5 with automatic gear system, MC6-Manual refers to motorcycle type 6 with manual gear system, MC7-Automatic refers to motorcycle type 7 with automatic gear system.

Particulate matter (PM) emissions from all motorcycle models decrease over time. For example, the MC5-Automatic starts at 486.28 µg/m^3 at 1 minute and drops to 131.75 µg/m^3 by 3 minutes, while the MC4-Automatic declines from 388.17 µg/m^3 to 121.20 µg/m^3. The MC2-Manual shows relatively high initial emissions at 559.50 µg/m^3, decreasing to 181.20 µg/m^3. Similarly, the MC7-Automatic drops from 503.45 µg/m^3 to 133.76 µg/m^3. The MC3-Automatic and MC6-Manual follow the same trend, with the MC6-Manual exhibiting the highest 1-minute emission (577.34 µg/m^3), reducing to 186.78 µg/m^3. Notably, the MC1-Automatic demonstrates the steepest overall reduction, falling from 406.95 µg/m^3 to just 97.91 µg/m^3. This consistent decline across all models suggests that motorcycle PM emissions are highest shortly after engine start and decrease as the engine continues running.

3.2 Fuel Type Differences (Welch's T-Test)

To evaluate the effect of fuel type on particulate matter (PM) emissions, an independent samples t-test was conducted comparing motorcycles fueled with Simple gasoline (n = 90) and Super gasoline (n = 45). Given the unequal sample sizes and potential differences in variance, the test was chosen to ensure a statistically robust comparison. The results indicated a highly significant difference in PM emissions between the two groups. Motorcycles using Simple gasoline emitted a mean PM concentration of 224.40 µg/m^3, whereas those using Super gasoline emitted a substantially lower mean of 17.12 µg/m^3. The t-statistic was 25.88 with a p-value of < 0.001, confirming a statistically significant difference at the 95% confidence level. It is important to note that although emissions peaked during the first minute due to incomplete combustion (cold-start phase), the third minute (min_3) better represents steady-state engine operation and thus forms the basis for comparative analysis in this study, a period known for elevated emission levels. Although full overnight engine soaking was not applied, each measurement was taken immediately after ignition, simulating real-world cold-start conditions in a semi-enclosed parking environment.

Despite the robustness of the t-test, the unequal sample sizes particularly the larger number of motorcycles using Simple gasoline pose a limitation in generalizing results for the Super gasoline group. Future research should aim for more balanced group sizes to enhance cross-group comparability. Nevertheless, the findings strongly suggest that using higher-grade fuels such as Super gasoline significantly reduces PM emissions, supporting policy initiatives aimed at improving fuel quality to mitigate urban air pollution.

Table 3. T-Test Results for Fuel Type

Fuel Type	Mean PM (µg/m^3)	Standard Deviation	Sample Size (n)	T-Statistics	P-Value
Simple	224.4	70.77	90	25.88	p < 0.001
Super	17.12	5.73	45	25.88	p < 0.001

Noted: The t-test confirms a statistically significant difference in average PM emissions between motorcycles using Simple and Super gasoline at the 95% confidence level ($p < 0.05$).

3.3 One-Way ANOVA Results

A one-way ANOVA was conducted to evaluate the impact of motorcycle age, engine size, and model type on PM emissions. The analysis found that motorcycle age significantly influenced emissions (F = 4.39, p = 0.015). Post-hoc testing using Tukey's HSD revealed that motorcycles aged 4–7 years emitted significantly more PM than those aged 0–3 years (mean difference = 67.19 µg/m^3, p = 0.016). There was no significant difference between the oldest group (8+ years) and the other two. This result suggests that engine performance tends to degrade sharply after three years of use, likely due to component wear and poor maintenance. Motorcycle model also showed a significant effect (F = 4.88, p = 0.0013). The MC1-Automatic emitted 170.14 µg/m^3 more PM than the MC5-Automatic (p = 0.001), indicating substantial variability between designs. Factors such as engine configuration, fuel system efficiency, and weight could contribute to this variation. In contrast, engine size (categorized as 100–110cc, 111–125cc, and 126–150cc) did not significantly affect PM emissions (F = 1.75, p = 0.179). This indicates that displacement alone is not a reliable predictor of emissions without considering additional operational or mechanical factors.

Table 4. One-Way ANOVA Summary

Factor	F-value	p-value	Tukey Comparison	Mean Diff (µg/m^3)	p-value
Age Group	4.39	0.015	0–3 vs 4–7 years	67.190	0.016
Engine Size Group	1.75	0.179	-	-	-
Motorcycle Type	4.88	0.0013	MC5 vs MC1	170.140	0.001

Noted: Results show statistically significant differences in PM emissions at a 95% confidence level ($p < 0.05$).

3.4 Two-Way ANOVA Results

To explore whether the effect of fuel type varied by motorcycle model, a two-way ANOVA with interaction was performed. The analysis confirmed significant main effects of fuel type ($F = 45.23$, $p < 0.001$) and motorcycle model ($F = 3.67$, $p = 0.009$), but the interaction effect between them was not statistically significant ($F = 1.12$, $p = 0.312$). This means that the benefit of using Super gasoline over Simple gasoline is consistent across all motorcycle models tested. In other words, the fuel effect does not depend on the specific motorcycle design, supporting the general policy recommendation of promoting higher-grade fuels across the entire motorcycle fleet.

The results of this study emphasize the critical role of fuel quality, vehicle age, and model type in shaping cold-start PM emissions from motorcycles. Fuel type had the strongest impact, reinforcing the need for fuel quality regulations. Mid-aged motorcycles (4–7 years old) contributed disproportionately to emissions, suggesting that inspection policies should begin targeting this age group. The identification of high-emitting models such as the MC1-Automatic further points to the potential of a model-specific emission grading system. While engine size was not a significant factor in this dataset, maintenance status, combustion efficiency, and fuel injection technology may have stronger explanatory power variables that should be explored in future work.

Table 5. Two-Way ANOVA Summary

Source of Variation	F-value	p-value	Significance ($\alpha = 0.05$)
Fuel Type	45.23	< 0.001	Significant
Motorcycle Model	3.67	0.009	Significant
Fuel Type × Motorcycle Model Interaction	1.12	0.312	Not Significant

4. DISCUSSION

This study confirms that certain motorcycle characteristics particularly vehicle age and model type are critical determinants of particulate matter (PM) emissions under cold-start conditions. Mid-aged motorcycles (4–7 years old) emitted significantly more PM than both newer and older motorcycles. The higher emissions from this age group are likely due to accumulated wear in combustion components such as piston rings, valves, and spark plugs, combined with inconsistent maintenance once warranties expire. These findings are consistent with studies in Bangkok and Hanoi, which found that motorcycles aged 5–7 years emitted substantially higher PM2.5 during idle and low-speed operation [4,9]. Model-specific differences were also statistically significant. The MC1-Automatic produced 170.14 µg/m^3 more PM than the MC5-Automatic, despite similar engine sizes. This suggests that design factors including combustion chamber geometry, fuel injection precision, and presence or absence of catalytic converters may outweigh displacement in determining emission performance. Such variability supports the case for model-specific emission standards rather than a one-size-fits-all approach. Notably, engine size was not a significant predictor of PM emissions, indicating that displacement alone is not an adequate regulatory criterion. Instead, operational efficiency, maintenance practices, and emissions control technologies appear to play a greater role.

Fuel type emerged as the most decisive factor influencing cold-start PM emissions. Motorcycles using Super gasoline emitted over 90% less PM than those using Simple gasoline, a difference confirmed by Welch's t-test ($p < 0.001$). The substantial reduction is likely due to higher octane ratings, lower sulfur content, and cleaner combustion properties of premium fuels. Conversely, motorcycles using mixed fuels (Simple/Super) emitted the highest PM levels across all time intervals exceeding 1,500 µg/m^3 during the first minute. This may result from inconsistent combustion properties caused by fuel mixing or variability in local fuel quality. Similar patterns have been reported in Vietnam and Indonesia, where substandard or blended fuels contributed to unstable combustion and elevated emissions [5,14]. These results strongly support fuel quality regulation as an immediate and low-barrier intervention for reducing PM emissions. Premium fuel promotion, combined with stricter fuel quality inspections, could significantly lower urban air pollution from two-wheelers.

Across all motorcycle categories, PM concentrations peaked in the first minute of idling averaging 564.50 µg/m^3 before declining by 71.8% within three minutes. This cold-start spike is a critical but often overlooked source of short-term, high-intensity exposure in semi-enclosed parking areas, were poor ventilation traps pollutants. Such exposure scenarios are of particular concern in university settings, where students and staff congregate daily. Given that the WHO 24-hour mean PM2.5 guideline is 15 µg/m^3, the first-minute cold-start concentrations measured in this study exceed safe limits by more than 35 times. This underscores the acute public health risk in environments with frequent engine starts.

Beyond gasoline motorcycles, the transition to electric motorcycles is often highlighted as a long-term solution for urban air quality, since they produce zero tailpipe emissions. However, their overall environmental impact cannot be fully assessed without considering lifecycle emissions, including electricity generation, battery production, and end-of-life management. Evidence from other Southeast Asian contexts suggests that the benefits of electrification depend heavily on the energy mix and waste management infrastructure. Therefore, while electrification presents a promising pathway for Cambodia's transport sector, further research should evaluate its lifecycle emissions before it can be considered a definitive strategy for reducing air pollution.

5. CONCLUSIONS

This study provides the first field-based assessment of motorcycle cold-start particulate matter (PM) emissions in Cambodia, conducted at the Institute of Technology of Cambodia. Findings reveal that PM levels spike sharply in the first minute of idling, exceeding 560 $\mu g/m^3$, before dropping by nearly two-thirds within three minutes. This highlights cold-starts as a critical but often overlooked source of short-term urban pollution. Fuel quality proved to be the most influential factor: Super gasoline cut emissions by over 90% compared to lower-grade fuels, while mid-aged motorcycles (4–7 years) were identified as the highest emitters. Model-specific differences further suggest that combustion design and technology significantly affect emission performance, whereas engine size alone was not a strong predictor. From a public health perspective, poorly ventilated parking areas can expose students and staff to acute risks that far exceed WHO guidelines. Policy measures should therefore prioritize upgrading fuel quality, strengthening inspections for mid-aged motorcycles, and establishing differentiated emission benchmarks. Awareness campaigns to discourage unnecessary idling and to promote cleaner fuels could also reduce exposure risks in high-density parking areas. Looking ahead, the transition to electric motorcycles could contribute to reducing Cambodia's urban air pollution, since they produce zero tailpipe emissions. However, their overall environmental benefits must be evaluated in terms of lifecycle emissions, including electricity generation, battery production, and end-of-life management.

While these findings are significant, the study is not without limitations. The analysis was confined to a single site, relied on uneven sample sizes, and focused only on idle cold-start emissions using instruments limited to PM detection. These constraints mean the results cannot fully capture the complexity of real-world motorcycle emissions. Future research should therefore expand to multiple study sites, include real driving conditions, and measure a wider range of pollutants such as CO, NOx, VOCs, and black carbon. In addition, evaluating the performance of low-emission and electric motorcycles will be essential. Although electric motorcycles produce zero tailpipe emissions, their overall environmental benefits depend on lifecycle factors. Incorporating lifecycle assessments will provide a more comprehensive foundation for cleaner technologies, stronger policies, and sustainable air quality management in Cambodia and beyond.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Institute of Technology of Cambodia (ITC) for institutional support and research facilities. This study was supported by the JICA Research Grant for LBE 2025 (Laboratory-Based Education). The authors also thank the faculty members, research assistants, and GTI students for their valuable contributions and assistance in data collection.

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