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The Impact of Window Openings on Indoor Air Quality in Public Toilets of Elementary School Buildings

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Abstract: This study examines the influence of window size and ventilation strategies on the IAQ (indoor air quality) of public toilets in elementary schools within Dhaka City. Maintaining adequate IAQ in school toilets is crucial, as poor air quality can pose significant health risks, including respiratory issues, discomfort, and increased susceptibility to infectious diseases. Moreover, substandard IAQ can lead to unpleasant odors and poor sanitation, negatively impacting students' overall well-being and learning environment. The research evaluates key IAQ indicators, including carbon dioxide (CO_2) and sulfur dioxide (SO_2) concentrations, humidity, and temperature, to determine the effectiveness of various ventilation setups. The study employs comparative analysis by varying window sizes and ventilation strategies, such as natural ventilation with different window opening percentages. Findings reveal that toilets with larger window areas and higher opening percentages achieve significantly improved natural ventilation, resulting in reduced levels of CO_2 and SO_2, lower humidity, and more stable temperatures. These improvements contribute to creating a more hygienic and comfortable environment. The results underscore the critical role of window design and placement in enhancing ventilation efficiency and minimizing pollutant buildup in public toilets. Based on these insights, the study provides actionable recommendations for optimizing window dimensions, placement, and ventilation strategies in the design of school toilets and facilities. By implementing these design improvements, schools can significantly enhance toilets sanitation, improve health outcomes for students, and create a more conducive learning environment. The findings offer practical solutions for addressing IAQ challenges in window design for architects and designers.

Key words: IAQ, window opening, ventilation effectiveness, CO_2 concentration, SO_2 concentration, temperature and humidity.

1. Introduction

Public toilets, particularly in elementary schools, require special attention to ensure good IAQ (indoor air quality) due to their frequent use by students. Poor IAQ in school restrooms can lead to unpleasant odours, discomfort, and potential health issues, as students spend a significant portion of their day within the school environment. Wilke [1] emphasizes that "the first step in creating a healthier and safer environment is in the washroom," underscoring the importance of managing IAQ to protect students' health and maintain hygiene. Proper ventilation and regular maintenance are critical in controlling harmful pollutants and ensuring hygienic conditions in these facilities. In toilet, window design plays a vital role in enhancing natural ventilation and improving IAQ. Optimizing window openings can reduce CO_2 concentrations and prevent the accumulation of indoor pollutants that can harm students' health. Research indicates that poorly ventilated classrooms, particularly those with inadequate window design, often experience elevated CO_2 levels, which are linked to cognitive impairment and respiratory issues [2-4]. Proper window placement, size, and operation are thus essential to promote airflow, maintain IAQ, and directly improve students' learning environments.

The significance of maintaining adequate ventilation in indoor spaces, especially classrooms, has been well-documented. CO_2 levels are widely used as an indicator of ventilation quality, reflecting the amount of air exhaled by occupants and providing insights into overall air exchange rates [5-7]. ASHRAE (American

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Society of Heating, Refrigerating and Air-Conditioning Engineers) [8] suggests that CO_2 levels should be interpreted with consideration for space type, occupancy, and other factors to determine appropriate ventilation requirements. Guidelines such as those from the European Committee for Standardization [9] and Gobierno de España [10] recommend that classroom CO_2 concentrations remain below 500 ppm above outdoor levels, aligning with IDA (Indoor Air Quality Design and Assessment) 2 ventilation quality standards. However, thresholds for infection risk vary based on contextual factors [11]. Studies like those by Peng and Jimenez [11] and Bazant et al. [12] model the relationship between CO_2 levels and infection risks. For example, the Harvard T.H. Chan School of Public Health advises maintaining 5 ACHs (air changes per hour) to minimize COVID-19 risks, which corresponds to approximately 700 ppm of CO_2 in typical classrooms [13].

Indoor CO_2 concentrations and their associated health risks have become a growing concern, particularly given the significant time spent indoors and the implications of COVID-19-related restrictions. Since CO_2 is exhaled by humans along with aerosolized particles containing viruses like SARS-CoV-2, it is considered a proxy for ventilation conditions and respiratory infection risks [14, 15]. Monitoring CO_2 levels is crucial for assessing the risk of respiratory diseases, including COVID-19 [16]. Elevated CO_2 levels can increase the relative risk of indoor infections, highlighting the importance of maintaining healthy CO_2 concentrations through adequate ventilation [17]. Thus, CO_2 serves as both an IAQ indicator and a pollutant, depending on its concentration and exposure duration [18]. Air pollution, particularly sulfur dioxide (SO_2), is a significant environmental factor contributing to CVDs (cardiovascular diseases) and hypertension [15, 19]. Exposure to SO_2 has been linked to increased oxidative stress, inflammation, and elevated blood pressure, all of which are associated with a higher risk of CVDs [20, 21]. Studies demonstrate that both short- and long-term exposure to SO_2 can increase hypertension-related hospital visits [22, 23]. The rising prevalence of air pollution in low- and middle-income countries further exacerbates the disease burden, necessitating a multi-pollutant approach to understand and mitigate health risks [24, 25].

Previous studies highlight the significant impact of window size and operation on ventilation and CO_2 concentrations, which directly affect IAQ. Larger windows enhance air exchange and reduce CO_2 levels, improving ventilation efficiency [26]. Conversely, smaller windows limit airflow, leading to higher CO_2 accumulation and poorer IAQ [23]. Effective window design, including size and opening methods, is essential for optimizing natural ventilation and maintaining healthy indoor CO_2 levels [16]. IAQ refers to the quality of air within and around buildings and structures, particularly concerning its impact on the health and comfort of occupants [15]. In recent years, both scientists and the public have shown growing concern about IAQ, given that people typically spend 70%-90% of their time indoors [8, 16]. Notably, several studies have highlighted that indoor air pollution levels often surpass outdoor levels [4, 18]. As a result, indoor air pollution poses greater health risks than outdoor air pollution, underscoring the importance of maintaining high IAQ at all times. One critical indoor space requiring attention is the toilet, a commonly used public facility. Maintaining good air quality in toilets is essential for hygiene and sanitation. This aligns with Wilke's [1] statement that "in order to create a healthier and safer environment, the first step is in the washroom".

Numerous studies have explored IAQ in toilets. For instance, Nakajima et al. [27] evaluated odor levels from portable toilets in a four-bed hospital ward. In this study, patients utilized a conventional portable toilet for a period of four consecutive days, followed by an odorless portable toilet for six consecutive days. Results indicated that the odorless portable toilet reduced pollutant levels, including a 14% decrease in hydrogen sulphide (H_2S), 30% less ammonia (NH_3), 58% fewer chemicals of light molecular weight, and 44% fewer chemicals of heavy molecular weight. Similarly, Jung et al. [28] examined flush toilet cleanliness at RGS (Raffles Girls' School). The study identified toilet wetness, the absence of litter bins and refuse lids, and a lack of ownership over toilet cleanliness as key factors contributing to hygiene and sanitation issues, which consequently affected the IAQ of RGS toilets. Additionally, Tsang [29] investigated gas emissions from dry toilets, which are toilets that use minimal or no water. The study reported average gas emissions of oxygen (O_2) concentrations close to ambient levels at 20.8%, hydrogen sulphide (H_2S) at 0.395 ppm, ammonium (NH_4) at 345 ppm, and ammonia (NH_3) at 7.9 ppm. External factors, such as wind speed and direction, also influence ventilation rates and the effectiveness of natural ventilation strategies [30]. In warm climates, natural ventilation can address thermal comfort issues while maintaining good IAQ. For instance, cross-ventilation through strategically placed windows can keep CO_2 concentrations below 1,000 ppm and ensure thermal comfort in Mediterranean climates [31]. In subtropical regions, where high temperatures and humidity prevail, maintaining indoor temperatures within an acceptable range (20.1-28.4 ℃) is critical for achieving thermal comfort and good IAQ [32]. However, natural ventilation is often limited by external environmental factors, requiring careful consideration of window size and placement to optimize its effectiveness [23].

These considerations raise important research questions: (a) Are new buildings designed to meet occupants' needs while neglecting IAQ? (b) Do buildings that prioritize IAQ show improvements in overall indoor conditions? This research underscores the significance of well-designed window sizes in enhancing IAQ in public restrooms. Additionally, a comparative analysis was carried out to assess compliance with relevant IAQ standards. The findings from this study provide valuable insights for building designers, offering practical strategies to improve IAQ and promote health and well-being.

1.1 Aims and Objectives

To investigate the impact of window size and ventilation on the IAQ of public toilets in elementary school buildings, with a focus on improving ventilation and reducing indoor air pollutants. The study has three main objectives:

(1) To assess the current IAQ parameters, including CO_2 concentration, SO_2 levels, humidity, and temperature, in public toilets with different window sizes and ventilation setups.

(2) To analyze the impact of window dimensions and their operational states (fully open, partially open, or closed) on natural ventilation efficiency and IAQ improvement, as well as their role in maintaining acceptable IAQ standards in public toilets.

(3) To optimize window size and ventilation strategies in public toilets within elementary schools to enhance IAQ and ensure greater user comfort.

How does window size design impact the IAQ of public toilets in Dhaka City?

Does the design and size of windows significantly influence the IAQ of public toilets in Dhaka City by improving ventilation efficiency and maintaining acceptable IAQ standards?

1.2 Literature Review

Here is a structured table chart (Table 1) summarizing the health effects of poor IAQ, with an emphasis on CO_2 concentration, SO_2 levels, temperature, and humidity, along with the standard ranges of these IAQ parameters and their potential health impacts in environments like school buildings and residential buildings.

Table 1 Literature based.

IAQ parameter	Health effect	Standard range	Explanation of health impact
CO_2 (carbon dioxide)	Respiratory discomfort, dizziness, shortness of breath, chronic lung conditions (e.g., asthma). Elevated CO_2 can worsen respiratory tract discomfort.	Below 1,000 ppm (safe)	Elevated CO_2 levels (above 1,000 ppm) can lead to symptoms like dizziness and shortness of breath, and may aggravate asthma.
SO_2 (sulfur dioxide)	Respiratory irritation, coughing, wheezing, difficulty in breathing. Long-term exposure may increase the risk of respiratory diseases.	Below 0.5 ppm (safe)	SO_2 can irritate the lungs, causing symptoms like wheezing, coughing, and difficulty in breathing. Chronic exposure can exacerbate asthma.
Humidity	Mold and mildew growth, which can trigger allergic reactions, asthma, and respiratory infections. High humidity also leads to dust mite proliferation.	30%-60% (ideal range)	Excessive humidity (above 60%) promotes mold growth, which can cause respiratory issues and exacerbate asthma or allergies.
Temperature	Heat stress, discomfort, fatigue, irritability, and decreased cognitive function (e.g., concentration issues in classrooms).	18-22 ℃ (ideal range)	High temperatures (above 25 ℃) combined with humidity can lead to discomfort, headaches, and reduced cognitive function, especially in schools.

2. Methodologies

This study used an experimental-comparative approach to evaluate the IAQ of public toilets in Dhaka, Bangladesh. Dhaka is characterized by a tropical wet and dry climate, with hot, wet, and humid conditions throughout the year. According to climate data from the local meteorological station, Dhaka experiences an annual average temperature of 25 ℃ (77 ℉), ranging from 18 ℃ (64 ℉) in January to 29 ℃ (84 ℉) in August. The monsoon season, which lasts from May to September, accounts for approximately 80% of the total annual rainfall, averaging 1,854 mm (73.0 inches). The study was conducted in four selected public toilets at an elementary school in Dhaka City. Among these, two toilets are designated for men, and the other two are for women. All selected toilets were ventilated by natural means through open windows. The characteristics of these toilets are detailed in Tables 2 and 3.

The investigation was carried out during break hours on a single day. Temperature, relative humidity, CO_2, and SO_2 levels were measured for 10-min intervals using an Air Quality Monitoring instrument. The instrument was placed vertically at a height of 1.3 m. During the study period, each of the investigated toilets was occupied.

Table 2 Measurement tools.

Feature	Specification
Model	TSI AIRASSURE 8144-6
Sensor type	NDIR (non-dispersive infrared)
Measurement range	400-10,000 ppm
Accuracy	±3% of reading + 30 ppm (typical)
Resolution	1 ppm
Monitored gases	Sulfur dioxide (SO_2), carbon dioxide (CO_2)
Environmental parameters	Temperature and relative humidity

Table 3 Indoor average temperature and humidity in summer 2024.

Month	Average temperature (℃)	Average humidity (%)
May	28.3	73%
June	28.2	78%
July	27.7	80%
August	28.2	80%
September	28.2	79%
Average	28.12	78%

3. Results and Discussion

Shown from the result in Table 4 and Fig. 1, Toilet 1 exhibits the widest temperature range (24.8 to 28.8 ℃) and the highest relative humidity levels (91% to 93%), indicating extreme conditions that may impact comfort and promote mold growth. Toilets 2 and 3 have relatively stable temperatures (26.4 to 27.5 ℃ and 26.6 to 26.9 ℃, respectively) with moderate humidity levels

(80% to 85% and 85% to 87%), while Toilet 4 experiences slightly higher temperatures (27.3 to 28.7 ℃) but the lowest humidity range (69% to 73%), These results could be affected from the climate of Dhaka in the tropical wet and dry climate.

Shown from the result in Table 5 and Fig. 2, the sulfur dioxide (SO_2) concentrations across the four toilets range from 0.01 to 0.05 ppm, with Toilet 1 showing the lowest levels (0.01-0.03 ppm), indicating minimal exposure, and Toilet 2 exhibiting the highest levels (0.03-0.05 ppm), suggesting relatively higher pollution, possibly due to poor ventilation or proximity to pollutant sources. Toilets 3 and 4 show moderate levels, both ranging from 0.03 to 0.04 ppm. These findings highlight the need for improved ventilation in areas with elevated SO_2 levels, particularly in Toilet 2, to mitigate potential health risks from prolonged exposure.

Table 4 Inside toilet average temperature and humidity.

Temperature (℃)	Min	Max	Relative humidity (%)	Min	Max
Toilet 1	24.8	28.8	Toilet 1	81	93
Toilet 2	26.4	27.5	Toilet 2	70	75
Toilet 3	26.6	26.9	Toilet 3	75	84
Toilet 4	27.3	28.7	Toilet 4	67	73

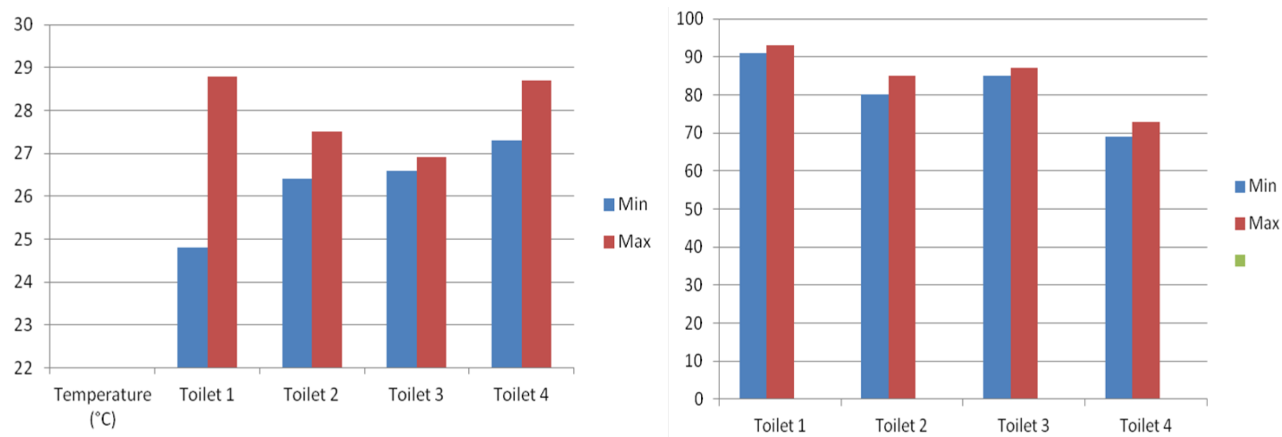

Fig. 1 Inside toilet average temperature and humidity.

Table 5 Inside toilet average sulfur dioxide (SO_2) and CO_2.

Sulfur dioxide (SO_2, ppm)	Min	Max	CO_2	Min	Max
Toilet 1	0.01	0.03	Toilet 1	400	440
Toilet 2	0.03	0.05	Toilet 2	600	750
Toilet 3	0.03	0.04	Toilet 3	500	650
Toilet 4	0.03	0.04	Toilet 4	500	680

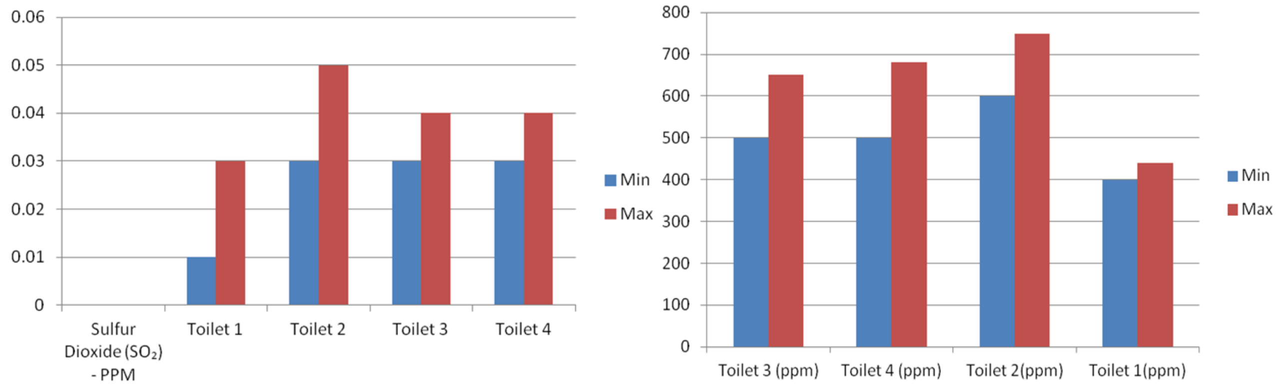

Fig. 2 Inside toilet average sulfur dioxide (SO_2) and CO_2.

Table 6 Time-averaged window opening area.

Toilet	Average CO_2 (ppm) (SD: standard deviation)	Min. average CO_2 (ppm)	Max. average CO_2 (ppm)	Window size ($H \times W$) (m)	Average window opening area (m^2)	Window area (m^2)
T1	897	901	1,003	0.5 × 1	0.5	0.2
T2	532	439	657	0.8 × 1	0.8	0.1
T3	733	447	905	0.9 × 0.95	0.85	0.1
T4	516	470	657	0.6 × 0.95	0.57	1

The data reveals varying CO_2 levels across different toilets, reflecting the impact of window openings and ventilation. Toilet 1 shows relatively low CO_2 levels (400 ppm to 440 ppm), suggesting effective ventilation and possibly larger or more open windows that allow for better airflow. In contrast, Toilets 2, 3, and 4 exhibit higher CO_2 concentrations (600-750 ppm), indicating that these spaces may have less effective natural ventilation, with CO_2 levels rising significantly when windows are closed. Toilet 2, in particular, shows the most substantial increase, highlighting the importance of maintaining open windows to ensure air exchange and reduce CO_2 buildup. Overall, the data emphasize that proper ventilation, including window openings, plays a critical role in controlling CO_2 concentrations and ensuring better IAQ.

Shown from Table 6, Toilet 1 exhibits the highest average CO_2 concentration (897 ppm), ranging from 901 ppm to 1,003 ppm, which may result from its small window area (0.2 m^2) limiting ventilation despite a relatively larger average window opening area (0.5 m^2). In contrast, Toilet 4 has the lowest average CO_2 concentration (516 ppm, 470-657 ppm), benefiting from the largest window area (1 m^2) and a moderate opening area (0.57 m^2), demonstrating the positive impact of larger windows on ventilation. Toilet 2 and Toilet 3 fall in between, with Toilet 2 showing a lower average CO_2 concentration (532 ppm, 439-657 ppm), likely due to its large opening area (0.8 m^2) despite the smallest window area (0.1 m^2), while Toilet 3 has a higher average CO_2 (733 ppm, 447-905 ppm), influenced by a moderate window area (0.1 m^2) and opening area (0.85 m^2). Overall, larger window areas and higher opening percentages, as seen in Toilet 4, significantly improve natural ventilation and reduce CO_2 levels. During the tests and field investigations, measuring the opening angle of bottom- and top-hinged windows provided sufficient precision for a qualitative assessment of window ventilation. Airflow through window openings is influenced not only by the size of the opening but also by the design and construction features of the window. Additional factors, such as wind speed and direction, the temperature difference between indoor and outdoor environments, the height of the opening, and curtain configurations, also play a significant role in determining airflow.

4. Conclusion

Toilet 4 demonstrates the most efficient ventilation, achieving the lowest average CO_2 concentration (516 ppm) due to its largest window area (1.0 m²), while Toilet 1 exhibits the highest CO_2 levels (897 ppm), likely caused by its smaller window area. Toilets 2 and 3 show intermediate CO_2 levels, influenced by their respective window sizes and opening areas. The findings emphasize that larger window areas and higher opening percentages significantly improve natural ventilation and reduce CO_2 concentrations. Poorly ventilated spaces, such as Toilets 1 and 2, highlight the need for design improvements, as window size, opening angle, and placement play crucial roles in enhancing airflow and ensuring better IAQ. By implementing these recommendations, schools can significantly improve the air quality and comfort in toilet facilities, promoting a healthier and more conducive learning environment.

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