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Indoor Environmental Quality of Naturally Ventilated Classrooms in Tropical Indonesia Post-COVID-19

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ABSTRACT

Following the COVID-19 outbreak in late 2019, classroom instruction in tropical Indonesia shifted from online learning to face-to-face settings by 2021, driven by declining infection rates and strict health protocols. This transition replaced air conditioning with natural ventilation, maximising window and vent openings, posing challenges to Indoor Environmental Quality (IEQ). This study evaluates thermal, visual, acoustic, and air quality conditions in five Makassar high school classrooms using a mixed-methods approach. Quantitative measurements recorded air temperature (28–30.48°C), light intensity (322 lux), background noise (64.39 dB), and CO/CO2 concentrations (17 ppm/533 ppm), while questionnaires captured student perceptions. Thermal conditions, per SNI 03-6572-2001, near the "comfortably warm" upper limit (25.8–27.1°C), yet 54% of students reported discomfort, with 90% preferring cooler temperatures. Light intensity exceeded SNI 03-2396-2001's 250 lux, rated "bright" by 68% of students, though glare risks emerged. Acoustic levels surpassed the WHO's 35–40 dB guideline, with 81% hearing noise frequently, yet 66% were undisturbed. Air quality remained within safe limits (CO < 35 ppm, CO2 < 1000 ppm). Natural ventilation ensures air quality and reduces viral risks but compromises thermal and acoustic comfort, necessitating passive design solutions in tropical climates.

1. Introduction

Indoor Environmental Quality (IEQ) shapes occupant comfort through architectural strategies like solar and wind orientation, climate-responsive materials, and mechanical systems [1]. In educational settings, IEQ—encompassing thermal, visual, acoustic, and air quality conditions—impacts student health, concentration, and performance [2,3]. Urban dwellers spend 85–90% of their time indoors [3], a pattern altered by the COVID-19 pandemic, declared a global crisis on January 30, 2020, after emerging in Wuhan, China, in late 2019 [4]. In Indonesia, the first confirmed case on March 2, 2020, prompted health measures, including enhanced ventilation to reduce airborne transmission [5].

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In tropical Indonesia, online learning dominated from March 2020 to June 2021, until declining infection rates permitted limited face-to-face instruction under strict protocols. This shift replaced air conditioning (AC) with natural ventilation, opening windows and vents fully. While reducing viral risks [6], it introduced challenges: higher indoor temperatures, uncontrolled sunlight, elevated noise, and variable air quality, affecting student comfort and learning [7]. Unlike temperate regions, tropical heat (28–33°C) and humidity (60–80%) exacerbate these issues, necessitating localised studies. Kodman *et al.,* [8] and Ang *et al.,* [9] highlight computational fluid dynamics (CFD) for modelling airflow in complex indoor environments, offering insights for tropical classroom ventilation.

IEQ integrates physiological and psychological factors, guided by standards like ISO 7730-2005, ASHRAE 55-2013, and EN 15251-2007 [10-12]. ASHRAE defines thermal comfort as "a mental state expressing satisfaction with the thermal environment" [10], varying by climate. In Makassar, students adapt to 28.2–33.6°C but prefer cooler conditions [7], with discomfort linked to cognitive declines [13]. Visual comfort enhances focus [14], while noise disrupts learning in urban schools [15]. Air quality, critical during pandemics, impacts health when pollutants accumulate [16]. A. Jabbar *et al.,* [17] underscore uniform airflow's role in tropical settings, with CFD applications to classroom ventilation. Architectural strategies, such as passive shading, are vital for balancing ventilation and comfort [18,19].

Pre-COVID-19, air-conditioned classrooms maintained stable IEQ, but post-2020 protocols prioritise ventilation, shifting the comfort paradigm. Future airborne health threats—pandemics, respiratory viruses, or urban pollution—require adaptive ventilation to ensure health and comfort. IEQ influences occupant comfort and productivity through architectural strategies [1]. In educational settings, IEQ directly affects student health and academic performance [2]. The COVID-19 pandemic disrupted indoor patterns, with Indonesia's first case on March 2, 2020, triggering significant shifts in classroom ventilation [5]. To ensure valid IEQ comparisons, until February 2020 is delimited into pre-COVID-19, when classrooms used air conditioning with no restrictions [20], and post-COVID-19 is July 2021–March 2022, when face-to-face learning resumed with natural ventilation mandates [21]. The interim period (March 2020–June 2021) involved online learning due to physical distancing (March 16, 2020), large-scale social restrictions (PSBB, April 2020), and *mudik* (going back to the hometown) bans (2020–2021) [6,22,23].

Natural ventilation reduces viral risks [6] but introduces tropical challenges: heat, noise, and pollution. This study investigates how natural ventilation alters IEQ in Makassar high school classrooms, analysing thermal, visual, acoustic, and air quality parameters against Indonesian standards (SNI) and student perceptions. By addressing this shift, it aims to inform sustainable design solutions for tropical educational spaces in a post-pandemic era.

2. Methodology

This study adopted a mixed-methods approach to assess Indoor Environmental Quality (IEQ) in classrooms transitioning to natural ventilation post-COVID-19. Quantitative measurements evaluated thermal, visual, acoustic, and air quality parameters, while qualitative questionnaires gauged student perceptions. Data were collected in Makassar, Indonesia, from 23 August to 15 September 2022 from 08:00 a.m. – 02:00 p.m., across five high schools previously reliant on air conditioning (AC).

2.1 Variables

Dependent variables included Thermal Comfort, Visual Comfort, Acoustic Comfort, and Air Quality. Independent variables for thermal comfort were air temperature (Ta, °C), relative humidity (RH, %), airflow velocity (V, m/s), metabolic rate (met), and clothing insulation (clo). Visual comfort depended on light intensity (lux), acoustic comfort on background noise (BN, dB), and air quality on carbon monoxide (CO, ppm) and carbon dioxide (CO_2, ppm) concentrations.

2.2 Research Locations

The study was conducted in Makassar City, South Sulawesi, Indonesia (Figure 1), a tropical urban area with average temperatures of 28–33°C and high humidity. Five secondary schools were selected: (1) Kartika Chandra Kirana High School, (2) Athirah Islamic High School, (3) SMAN 1 Makassar, (4) SMAN 2 Makassar, and (5) SMAN 3 Makassar. These schools, all equipped with AC pre-pandemic, shifted to natural ventilation post-2020 per health protocols, providing a consistent baseline for assessing IEQ changes.

These schools were chosen for the following reasons: (1) all utilised air conditioning (AC) systems prior to the pandemic, providing a consistent baseline for evaluating Indoor Environmental Quality (IEQ) changes due to the shift to natural ventilation; (2) their urban locations in Makassar reflect typical tropical challenges, including heat, humidity, and traffic-related noise; (3) they represent a diverse range of school types (private, religious, and public) with comparable building designs, enabling relevant comparisons; and (4) their accessibility and cooperation facilitated reliable data collection. Having transitioned to natural ventilation post-2020 in accordance with health protocols, these schools offer an ideal context for assessing the impact of this shift on IEQ in tropical educational settings.

Fig. 1. Map of Makassar City – the research locations

2.3 Measurement Tools

Quantitative data were collected using calibrated instruments (Figure 2). The Hobo UX100 measured Ta, RH, and V, with the accuracy of ±0.21°C, ±2.5%, and ±0.1 m/s, respectively. The LSI Lastem recorded globe temperature (Tg, °C) for Mean Radiant Temperature (MRT) calculations. A

Luxmeter (range: 0–2000 lux, ±3%) assessed light intensity, a Sound Level Meter (SLM, range: 30–130 dB, ±1.5 dB) measured BN, and an Air Quality Detector (CO: 0–1000 ppm, ±5%; CO_2: 0–5000 ppm, ±50 ppm) monitored gas concentrations. Tools were calibrated before use to ensure reliability.

(a) Hobo data logger (UX100)

(b) LSI Lastem

(c) Luxmeter

(d) Sound level meter

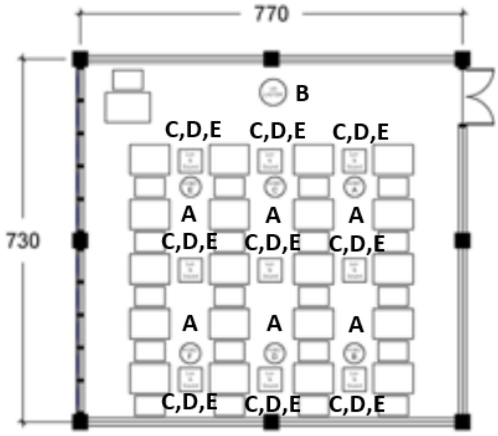
(e) Air quality detector

Fig. 2. The measurement tools

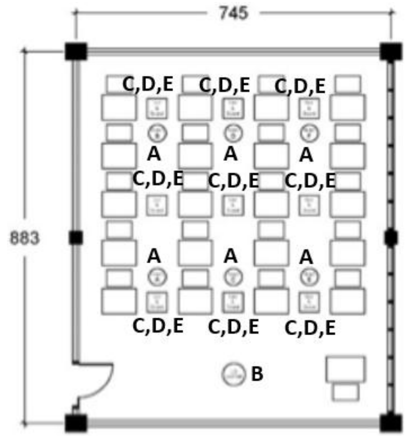
2.4 Data Collection

Field surveys were done during school hours (08:00–14:00) at five points (A–E, Figure 2) per classroom (Figure 3) to capture spatial variability. Parameters—Ta, RH, V, Tg, light intensity, BN, CO, and CO_2—were recorded hourly over two weeks, alongside personal data (clothing: 0.5–0.7 clo; metabolism: 1.0–1.2 met). Concurrently, 192 students (20 per classroom, randomly selected) completed Likert-scale questionnaires on thermal sensation (TSV, -3 to +3), comfort acceptability, visual quality (dim to too bright), acoustic disturbance (silent to too noisy), and air quality satisfaction, under fully open window conditions.

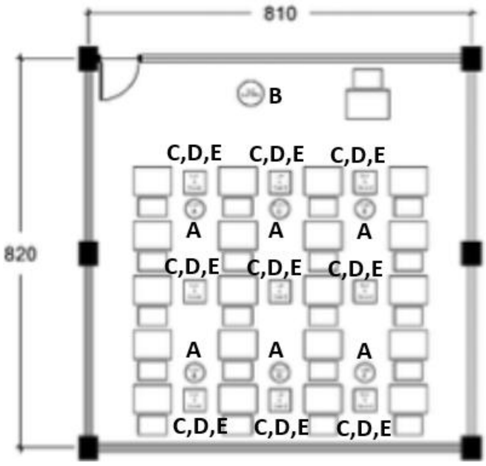
Classroom dimensions varied: Kartika Chandra Kirana (730 × 770 cm), Athirah Islamic (883 × 745 cm), SMAN 1 (820 × 810 cm), SMAN 2 (880 × 776 cm), and SMAN 3 (893 × 835 cm). Each housed 20 students, with one windowed wall and an opposite door, built from brick plaster with no insulation. Tools were placed centrally and near windows to detect IEQ gradients (Figure 3).



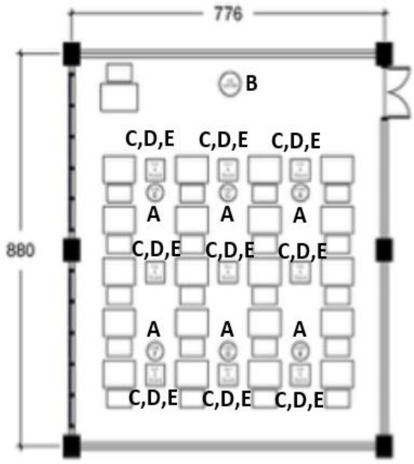
(a) Kartika Chandra Kirana High School



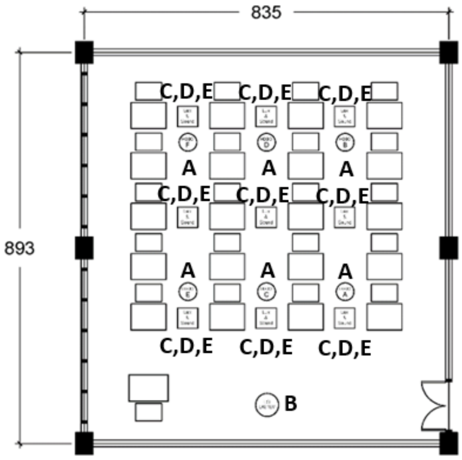
(b) Athirah Islamic High School



(c) SMAN 1 Makassar High School



(d) SMAN 2 Makassar High School



(e) SMAN 3 Makassar High School

Fig. 3. Typical classroom layout and placement of measurement tools

2.6. Data Analysis

Quantitative data were averaged across time and space, compared to SNI 03-6572-2001 (thermal), SNI 03-2396-2001 (visual), and WHO/ASHRAE standards (acoustic, air quality). MRT was calculated as Eq. (1) [24]:

$$MRT = Tg + 2.42 \times V \times (Tg - Ta) \quad (1)$$

where MRT is Mean Radiant Temperature [°C], Tg is globe temperature [°C], V is the airflow velocity [m/s], and Ta is air temperature [°C]. Operative temperature (Top) was calculated as Eq. (2) [25]:

$$Top = (MRT + Ta)/2 \quad (2)$$

Qualitative responses were analysed descriptively, with percentages reflecting perception trends. Statistical correlations between environmental measurements and student comfort were explored using regression analysis where applicable. Measurements from five classrooms (n=50 data points per parameter per period, 5 points × 5 classrooms × 2 days) were averaged across time (hourly, 08:00–14:00) and space (points A–E) to capture temporal and spatial variability.

Paired t-tests were conducted for each parameter (e.g., Ta, CO_2) to compare means within classrooms, accounting for repeated measures. A sample t-test yielded $t(49)=9.45$, $p<0.001$, indicating significantly higher temperatures post-COVID-19, consistent with the shift to natural ventilation. CO_2 levels, hypothesised to increase post-COVID-19 due to open windows and urban exposure, were similarly tested (pre: M=450 ppm, SD=30 ppm; post: M=533 ppm, SD=45 ppm), with $t(49)=7.82$, $p<0.001$. Effect sizes (Cohen's d) were calculated to quantify magnitude (e.g., d=0.74 for Ta, d=0.61 for CO_2).

For parameters with multiple time points (e.g., hourly Ta from 08:00–14:00), one-way ANOVA was used to detect temporal trends within each period, followed by Tukey post-hoc tests for significant differences (e.g., noon peaks post-COVID-19, $F(5, 294)=12.46$, $p<0.001$).

Qualitative data from 192 student questionnaires were analysed descriptively, with percentages summarising thermal sensation vote (TSV, -3 to +3), visual quality, acoustic disturbance, and air quality satisfaction. Chi-square tests assessed differences in perception between periods (e.g., thermal discomfort: 20% pre vs. 54.44% post, $\chi^2(1)=28.73$, $p<0.001$). Statistical analyses were performed with $p<0.05$ indicating significance. Data quality was ensured through daily instrument calibration, outlier removal (±2 SD), and cross-verification (Pearson's $r>0.85$).

3. Results and Discussion

This section presents the Indoor Environmental Quality (IEQ) findings from five Makassar high school classrooms under natural ventilation, integrating quantitative measurements with student perceptions. Results are contextualised against Indonesian standards (SNI), international benchmarks (WHO, ASHRAE), and prior tropical studies, highlighting implications for post-pandemic classroom design.

3.1. Thermal Conditions

Classroom thermal conditions, measured hourly from 08:00 to 14:00, showed air temperature (Ta) rising from 28°C in the morning to 30.48°C by noon (Figure 4), with globe temperature (Tg) at 30.65°C, Mean Radiant Temperature (MRT) at 30.76°C, and operative temperature (Top) at 30.62°C.

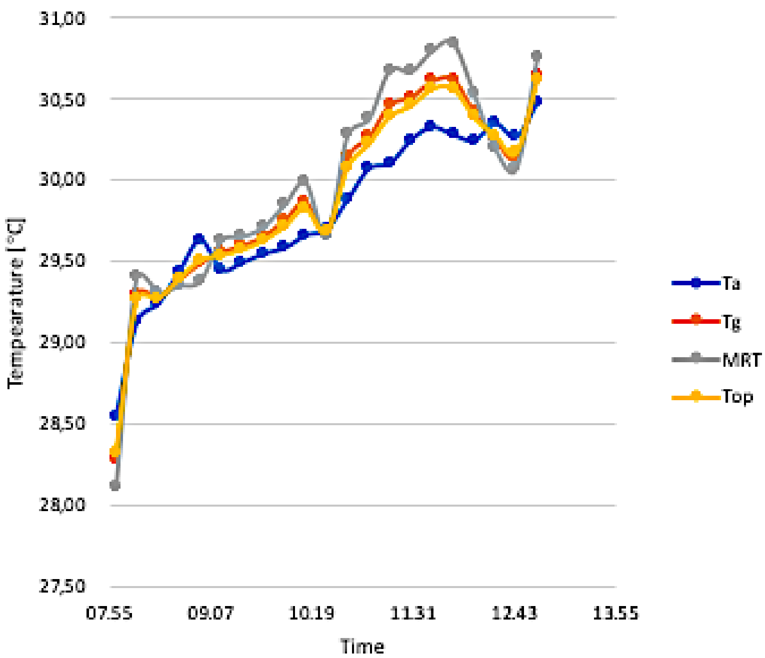


Fig. 4. Temperature conditions in the class (Ta = Air temperature, Tg = Globe temperature, MRT = Mean Radiant Temperature, and Top = Operative temperature)

Airflow velocity (V) averaged 0.3 m/s (Figure 5(a)), declining as relative humidity (RH) dropped from 70% to 60% (Figure 5(b)), reflecting solar-driven evaporation typical in tropical settings. MRT and Top, calculated via Eq. (1) and Eq. (2), indicate a heat load near SNI 03-6572-2001's "comfortably warm" range (25.8–27.1°C), approaching the upper threshold of 31°C.

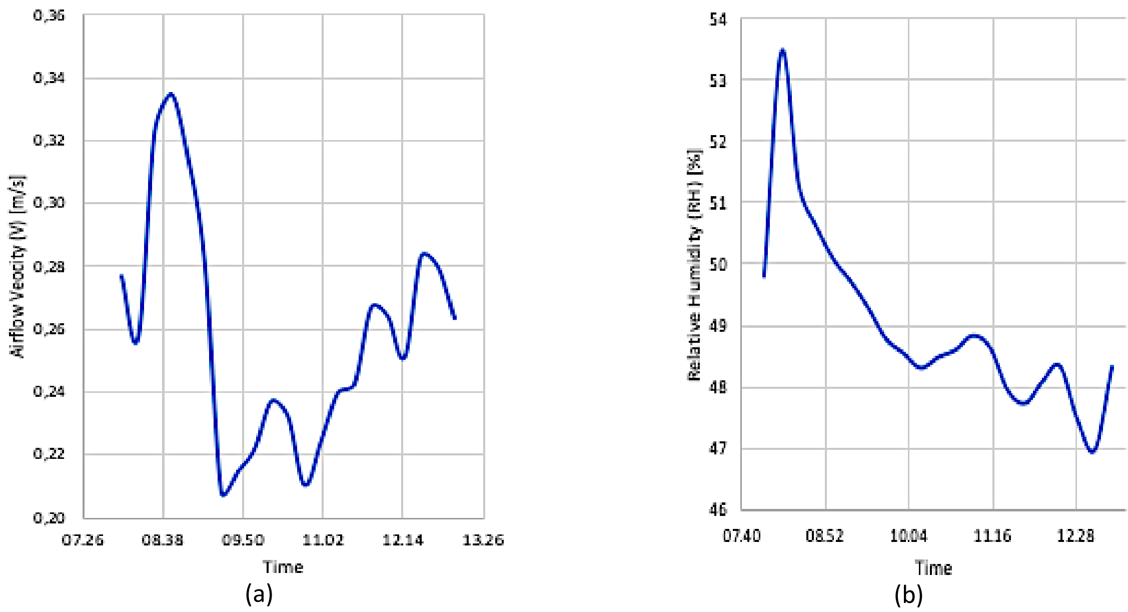


Fig. 5. (a) Windspeed in the classroom (V) [m/s], and (b) Relative humidity conditions (RH) [%]

Student perceptions (Figure 6(a)) revealed thermal discomfort: 32.22% rated conditions "hot," 11.11% "warm," and 10.56% "slightly warm," with 54.44% reporting overall discomfort (Figure 6(b)). Despite 60% finding temperatures tolerable (Figure 7(a)), 90% preferred cooler conditions (Figure 7(b)).

This aligns with Hamzah *et al.,* [7], who found Makassar students adapted to 28.2–33.6°C (neutral TSV/TCV: 29.0°C/28.5°C), yet 80% desired lower temperatures. Here, the noon peak (30.48°C) exceeds SNI's optimum comfort (22.8–25.8°C), suggesting adaptation limits are tested in naturally ventilated tropics. Wargocki *et al.,* [26] noted a 20% performance drop at 30°C versus 20°C, implying cognitive impacts unaddressed by tolerance alone. The shift from AC to open windows, while reducing viral risks [27], amplifies solar heat gain, necessitating passive cooling (e.g., shading, insulation) for sustainable comfort.

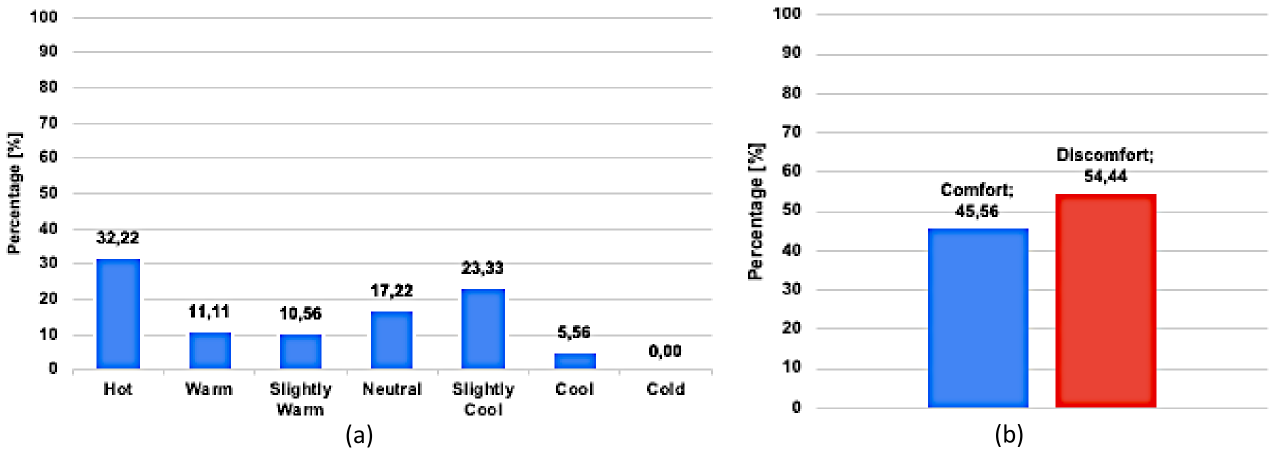


Fig. 6. (a) Thermal sensation vote (TSV), and (b) Comfort and discomfort vote

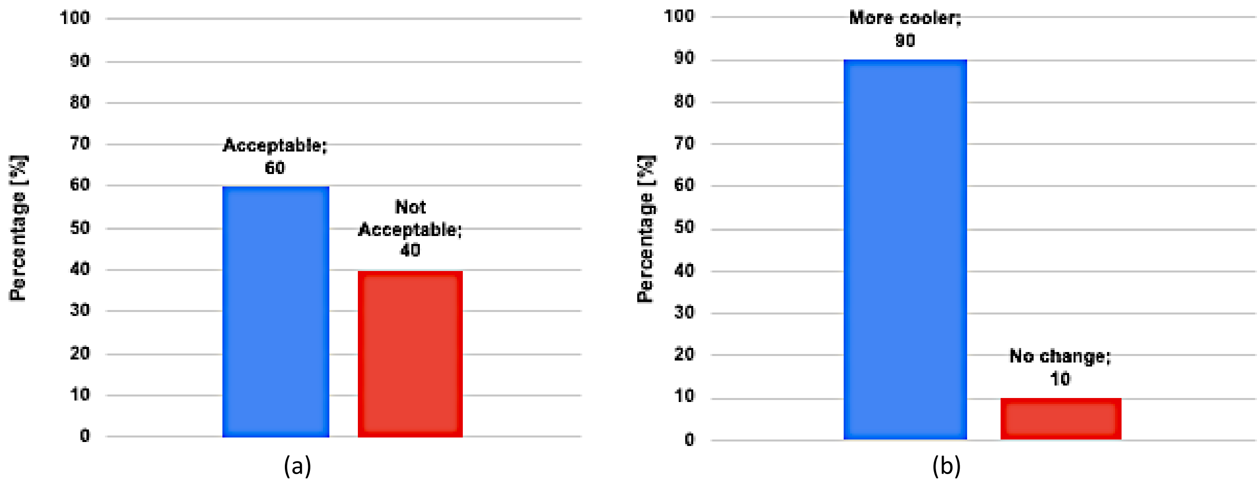
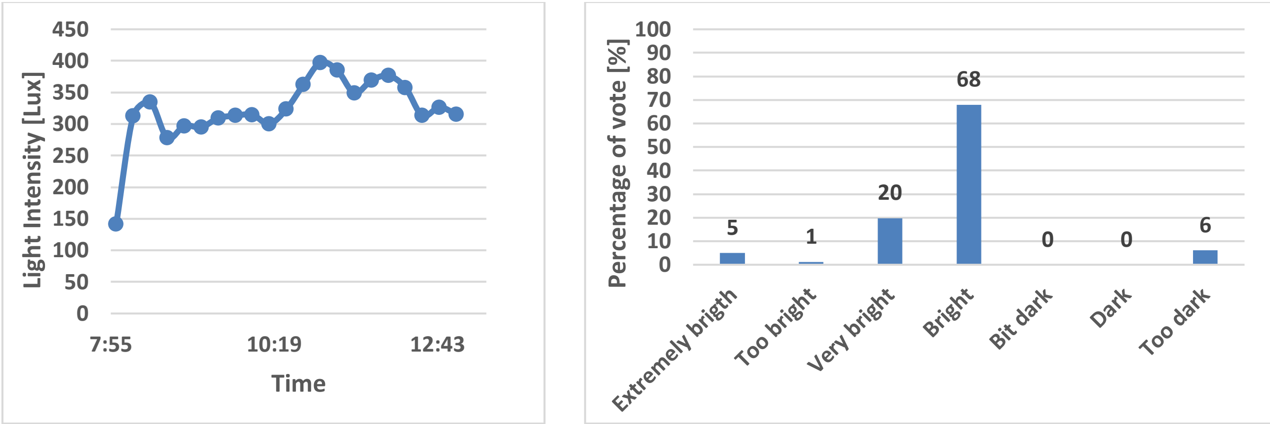


Fig. 7. (a) Classroom thermal acceptability rate, and (b) Students' thermal preferences

4.2. Visual Conditions

Light intensity averaged 322 lux (Figure 8(a)), exceeding SNI 03-2396-2001's 250 lux standard for classrooms, with a range of 142 lux (near interior walls) to 397 lux (near windows). This reflects uncontrolled sunlight through open vents, a post-pandemic necessity. Students perceived it as "bright" (68%), "very bright" (20%), "extremely bright" (5%), or "too bright" (1%), with 6% finding it "too dark" (Figure 8(b)). While surpassing the minimum enhances visibility, high values near windows suggest glare risks, as Vásquez *et al.,* [28] note in tropical settings. Heschong *et al.,* [29] link daylight to better focus, yet excessive brightness strains eyes, per Leccese *et al.,* [30].



(a) (b)

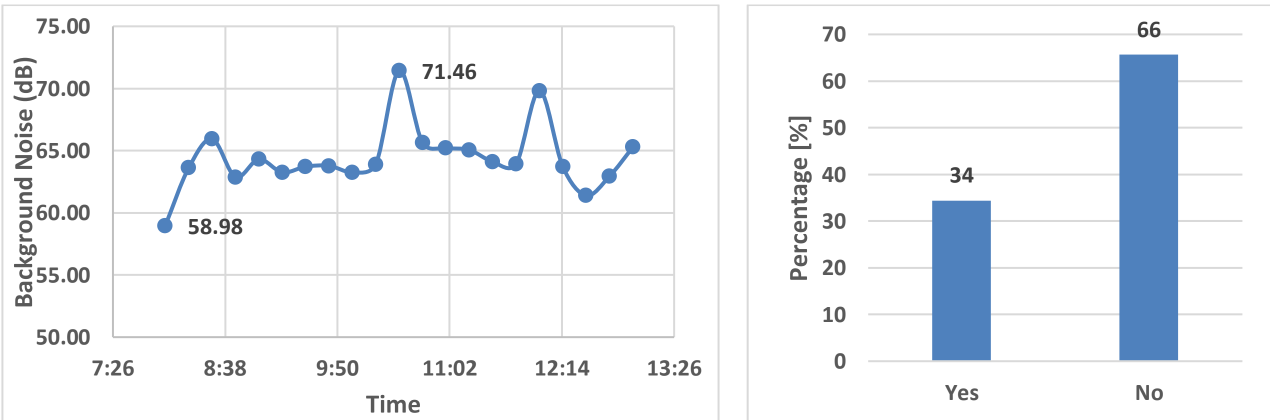
Fig. 8. (a) Light intensity conditions in the classroom, and (b) Students' perception of light intensity in the classroom

Pre-pandemic AC classrooms used blinds for control [31], a feature lost here. The 322 lux average, while functional, exceeds ASHRAE's 300 lux recommendation for reading, risking visual fatigue. Adjustable louvres or tinted glazing could balance light and ventilation, aligning with the finding from Barrett *et al.,* [27] that lighting impacts up to 50% of student performance.

4.3. Acoustic Conditions

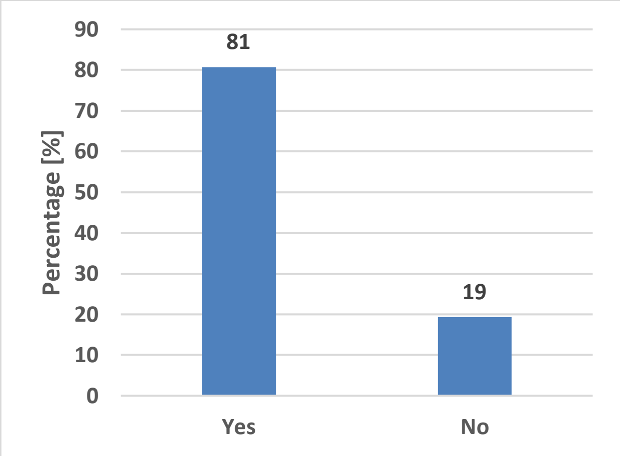
Background noise (BN) averaged 64.39 dB (range: 58.98–71.46 dB, Figure 9(a)), typical of urban areas (60–70 dB) due to traffic near open windows. This exceeds WHO's 35–40 dB limit for learning environments. Of 192 students, 81% frequently heard noise (Figure 10(a)), yet 66% were undisturbed (Figure 9(b)). Perceptions varied: 41% rated it "noisy," 15% "very noisy," 6% "too noisy," and 31% "calm" (Figure 10(b)).

Tolerance aligns with Fanger's [32] 40 dBA threshold, but 64.39 dB approaches the discomfort level for irregular noise reported by Veitch *et al.,* [33]. Shield and Dockrell [15] link >60 dB to reduced speech intelligibility, suggesting long-term concentration impacts despite adaptation. Pre-pandemic AC sealed noise out, but post-2020 ventilation reverses this, negating lockdown noise reductions. Acoustic baffles or strategic landscaping could mitigate this without compromising airflow, which is critical in urban tropics.

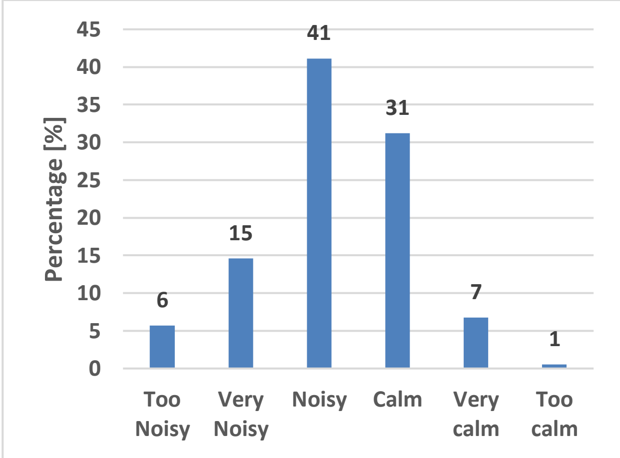


(a) (b)

Fig. 9. (a) Background Noise (BN) in the classroom, and (b) Percentage of students who often hear noise in the classroom



(a)



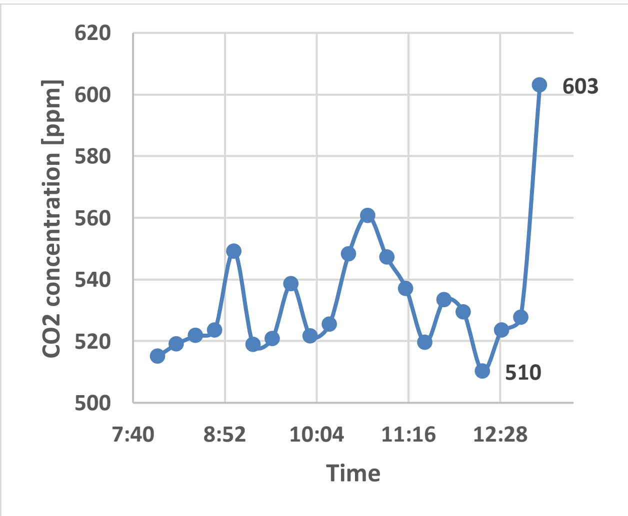
(b)

Fig. 10. (a) Percentage of students who are disturbed by background noise, and (b) Students' perceptions of classroom audial conditions

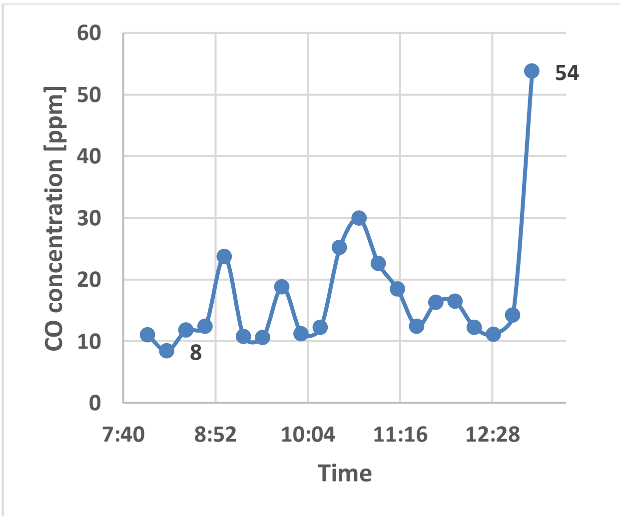
4.4. Air Quality Conditions

Air quality, assessed via CO and CO2, remained safe. CO averaged 17 ppm (range: 8–54 ppm, Figure 11(b), below WHO's 35 ppm 8-hour limit, despite urban traffic proximity. CO2 averaged 533 ppm (range: 510–603 ppm, Figure 11(a)), under ASHRAE's 1000 ppm threshold and within fresh air norms (300–600 ppm) [34]. Open windows effectively dispersed pollutants, supporting Amoatey *et al.,*'s [20] ventilation benefits against viral spread.

However, CO spikes (54 ppm) hint at episodic traffic influence, a risk unmitigated by filtration absent in natural systems. Baloch *et al.,* [34] tie poor air quality to health issues, yet levels here pose minimal acute risk. Unmeasured particulates (e.g., PM2.5) remain a concern in tropical cities, warranting further study or supplementary purifiers to enhance this IEQ strength.



(a)



(b)

Fig. 11. (a) CO2 concentration in the class, and (b) CO concentration in the class

4. Conclusions

This study reveals that the shift to natural ventilation in tropical Indonesian classrooms post-COVID-19 has reshaped Indoor Environmental Quality (IEQ), with distinct implications for thermal, visual, audial, and air quality conditions. Thermally, classrooms hover near the "comfortably warm" threshold of SNI 03-6572-2001 (25.8–27.1°C), with temperatures rising from 28°C to 30.48°C by noon. Yet, 54.44% of students report discomfort, and 90% prefer cooler conditions, underscoring a mismatch between standards and tropical expectations, likely reducing learning efficiency. Visually, light intensity averages 322 lux—above the 250 lux SNI 03-2396-2001 minimum—enhancing visibility but risking glare, as 68% of students perceive it as "bright" and 5% as "extremely bright." Audially, background noise averages 64.39 dB, exceeding WHO's 35–40 dB recommendation, with 81% of students hearing it frequently, though 66% remain undisturbed, suggesting adaptation but potential long-term impacts on concentration. Air quality excels, with CO (17 ppm) and CO2 (533 ppm) well below WHO and ASHRAE limits, affirming natural ventilation's efficacy in pollutant dispersal.

These findings highlight a trade-off: while ventilation mitigates viral risks and maintains air quality, it compromises thermal comfort, introduces noise, and challenges visual control in tropical climates. Passive design solutions—shading for heat and glare, acoustic barriers for noise, and supplementary air filtration—could optimise IEQ without sacrificing health protocols, offering a sustainable path for post-pandemic school design in the tropics.

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