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# Analysis of Indoor Air Quality in the Laboratories of Poltekkes Riau

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**Abstract**

This study examines indoor air quality (IAQ) in Poltekkes Riau's laboratory building through systematic measurement of six parameters: $CO_2$, HCHO, TVOC, PM1.0, PM2.5, and PM10 per Minister of Health Regulation No. 48/2016. Direct measurements were conducted in ten laboratories under three operational conditions (active use, no activity, ventilation shutdown) across different time intervals. Results reveal significant deviations from standards: 60% of spaces exceeded $CO_2$ limits during active use, while PM2.5 and PM10 exceeded thresholds in 90% of measured spaces. Notably, 70% of rooms exceeded formaldehyde limits and 80% exceeded TVOC limits, particularly in spaces with MDF materials. Original findings document passive off-gassing phenomena where formaldehyde peaked during non-occupancy periods, and establish correlations between architectural features and multi-pollutant accumulation. Recommendations include strategic exhaust fan placement, low-VOC materials, and cross-ventilation systems for tropical educational environments, supporting the urgent need for updated building regulations addressing multi-pollutant environments in health education facilities.

**Keywords:** *formaldehyde emissions; health education laboratory; indoor air quality; material off-gassing; minister of health regulation no. 48/2016; multi-pollutant assessment; tropical climate adaptation; ventilation design*

## Introduction

Indoor Air Quality (IAQ) has become a primary concern in the design of healthy learning environments, particularly in vocational education facilities such as laboratories. According to (Bronfenbrenner, 1979) The physical environment—including indoor air—is a key component of the human ecological system that affects health and productivity.

The selection of health education laboratories as the research focus stems from their unique environmental characteristics that present distinct IAQ challenges compared to conventional educational spaces. Health polytechnic laboratories represent high-risk environments due to three critical factors: (1) intensive chemical usage in practical sessions, (2) high occupancy density exceeding standard spatial requirements (often below 2 m² per person), and (3) specialized interior materials that contribute to pollutant emissions. Unlike general classrooms, these facilities routinely handle biological specimens, chemical reagents, and medical equipment that release volatile compounds even during non-operational periods—a phenomenon documented as "passive off-gassing" in recent building science literature (Salthammer, 1997).

Particularly concerning is the prevalence of formaldehyde emissions from medium-density fiberboard (MDF) cabinetry commonly used in Indonesian health education facilities. Preliminary investigations revealed that 70% of laboratory spaces exceeded WHO's formaldehyde threshold (100 ppb) even during unoccupied periods, indicating persistent material-based emissions that standard ventilation protocols fail to address (Agarwal et al., 2024). This finding aligns with global concerns raised by the International Living Future Institute (ILFI, 2023), which identifies health education facilities as "critical infrastructure requiring specialized IAQ management" due to their dual role in training future healthcare professionals and serving as clinical environments.

The urgency of this research is further amplified by Indonesia's tropical climate, where high humidity accelerates off-gassing from building materials while simultaneously compromising natural ventilation effectiveness—a combination that creates uniquely challenging IAQ conditions in educational laboratories that existing regulations fail to adequately address (Joseph Manuel, Full Member ASHRAE; Deniz Besiktepe. PhD; Anthony E Sparkling, 2024).

As enclosed spaces, laboratories are prone to the accumulation of pollutants such as carbon dioxide ($CO_2$), formaldehyde (HCHO), total volatile organic compounds (TVOCs), and airborne particulates PM1.0, PM2.5, and PM10. These pollutants risk triggering Sick Building Syndrome (SBS), a health condition caused by poor indoor air quality. (Salthammer, 1997). The Riau Health Polytechnic (Poltekkes Riau) has a laboratory building that has been in operation for more than a decade and is classified as an existing building.

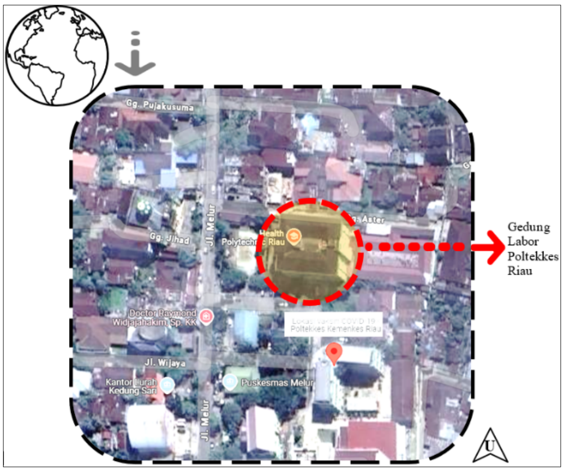


**Figure 1.** Research Location: Laboratory Building of Riau Health Polytechnic
Source: Author, 2025

**Figure 2.** Photographic Documentation of the Existing Laboratory Building
Source: Author, 2025

This study aims to analyze the air quality in ten laboratory rooms located on the first and second floors of the Poltekkes Riau Laboratory Building, based on the standards set by the Indonesian Ministry of Health Regulation No. 48 of 2016.

**Table 1.** Summary of Air Pollutant Parameters and Threshold Limits (Regulation of the Minister of Health No. 48 of 2016)

| No | Parameter | Unit | Permissible Exposure Limit |
|---|---|---|---|
| **1** | Karbon Dioksida ($CO_2$) | ppm | 350 – 1000 ppm |
| **2** | Formaldehida (HCHO) | µg/m³ | ≤ 120 µg/m³ *(≈ 100 ppb)* |
| **3** | Total Volatile Organic Compounds (TVOC) | mg/m³ | ≤ 3 mg/m³ *(≈ 3.690 µg/m³)* |
| **4** | Fine Particulates matter PM1.0 | µg/m³ | ≤ 10 µg/m³ *(Based on the WHO guideline)* |
| **5** | Fine Particulates matter PM2.5 | µg/m³ | ≤ 50 µg/m³ *(Converted from 0.05 mg/m³)* |
| **6** | Fine Particulates matter PM10 | µg/m³ | ≤ 150 µg/m³ *(Converted from 0.15 mg/m³)* |

Source: Author, 2025

This study also evaluates the effectiveness of the ventilation system, the impact of user density, and the contribution of interior materials to the increase in pollutants. Accordingly, the results of this study are expected to serve as a preliminary reference for architectural interventions and ventilation technology improvements in the pursuit of healthy and sustainable laboratory spaces.

# Literature Review

### Indoor Air Quality

Indoor air quality is a crucial parameter in creating a healthy, productive, and comfortable learning environment. According to (Salthammer, 1997)The key parameters of air quality include gas content (such as $CO_2$), chemical compounds (such as formaldehyde and TVOCs), and particulates (PM1.0, PM2.5, and PM10). These pollutants may originate from user activities, inadequate ventilation, as well as interior materials such as MDF and emulsion paints that contain volatile compounds. High concentrations of these pollutants can lead to Sick Building Syndrome (SBS), a range of mild to severe health symptoms caused by polluted air in enclosed indoor spaces. (WHO, 1982).

### Ambient Air Quality Standards

**Table 2.** Air Quality Parameter Limits in Regulation of the Minister of Health No. 48 of 2016

| Air Quality Factors | Standard Thresholds | | Measuring Instruments |
|---|---|---|---|
| **Karbondioksida ($CO_2$)** | ASHRAE 55-2017/WHO Air Quality Guidelines 2021/Permenkes 48-2016 | 350ppm ~ 1000ppm | $CO_2$ Meter |
| **Formaldehyde (HCHO)** | Permenkes 48-2016 | ≤ 120 µg/m³ or approximately 100 ppb (parts per billion) or 97.7ppm | HCHO Meter |
| **Total Volatile Organic Compounds (TVOC)** | Permenkes 48-2016 | 3ppm = 3,69 mg/m³ or 3690 µg/m³ | TVOC Meter |
| **Airborne Particulate Matter PM1.0** | WHO Air Quality Guidelines 2021/Permenkes 48-2016 | ≤0.01 mg/m³ or 10 µm/m³ | PM Meter |
| **Airborne Particulate Matter PM2.5** | WHO Air Quality Guidelines 2021/Permenkes 48-2016 | ≤0.05 mg/m³ or 50 µm/m³ | |
| **Airborne Particulate Matter PM10** | WHO Air Quality Guidelines 2021/Permenkes 48-2016 | ≤0.15 mg/m³ or 150 µm/m³ | |

Source: Author, 2025

The primary regulation referenced in this study is Minister of Health Regulation No. 48 of 2016, which sets the threshold limits for indoor air quality in healthcare facility buildings and health education institutions. The standard parameters referred to include:

- $CO_2$: 350–1000 ppm

- Formaldehida (HCHO): ≤ 120 μg/m³
- TVOC: ≤ 3 ppm (≈ 3.690 μg/m³)
- PM1.0: ≤ 10 μg/m³
- PM2.5: ≤ 50 μg/m³
- PM10: ≤ 150 μg/m³

**Environmental Theory and Architectural Approach**

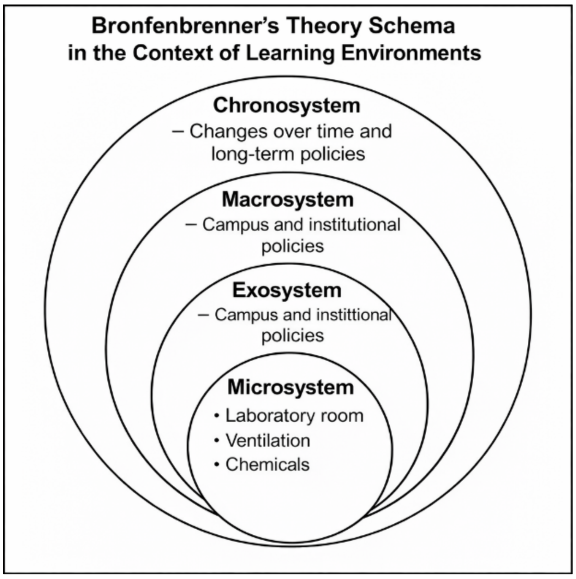


**Figure 3.** Human Ecology Theory
Source: Bronfenbrenner, 1979

This study also refers to the Human Ecology Theory by (Bronfenbrenner, 1979), which emphasizes the importance of the microsystem environment, such as learning spaces, in shaping individual health and behavior. Air quality, as part of the microsystem, significantly influences cognitive performance, thermal comfort, and users' health perceptions. On the other hand, architectural approaches such as cross-ventilation design, the selection of low-emission interior materials, and standardized HVAC systems can serve as effective solutions to improve air quality in line with the green building concept. (GBCI, 2018).

**Related Studies**

Several previous studies have highlighted the importance of evaluating air quality in learning environments. (Munawaroh & Elbes, 2019) Found that thermal comfort and air quality in mosque spaces depend on ventilation patterns and the number of occupants. Meanwhile, (Latif et al., 2023) Emphasized the importance of airflow management in circulation areas such as corridors and voids through the use of exhaust fan systems to reduce heat buildup and pollutant accumulation.

**Table 3.** Comparative Study of Indoor Air Quality in Educational Settings from Various Sources

| No | Researcher & Year | Research Location | Parameters Assessed | Key Findings |
|---|---|---|---|---|
| **1** | Munawaroh et al. (2023) | Masjid Ad-Du'a, Bandar Lampung | Temperature, humidity, and air velocity, PMV, PPD | The air and thermal quality do not meet the standards of ASHRAE & SNI |
| **2** | Latif (2023) | Corridor space & void, Unhas Gowa | Airflow, mechanical ventilation (exhaust fan) | Ineffective circulation in the void area; stack effect dominant |
| **3** | Salthammer et al. (2010) | Review Global | TVOC, formaldehyde, and building materials | High VOC emissions from MDF and paint; the need for cross ventilation |

Source: Author, 2025

**Laboratory-Specific IAQ Challenges: Beyond Regulatory Compliance.**

While Minister of Health Regulation No. 48 of 2016 establishes essential IAQ parameters for healthcare and health education facilities in Indonesia, its implementation reveals significant gaps when applied to specialized environments like health polytechnic laboratories. The regulation primarily addresses single-pollutant thresholds without considering synergistic effects that occur in laboratory settings, where multiple contaminants—chemical residues, biological agents, and particulate matter—interact to create complex exposure scenarios (Agarwal et al., 2024). Recent studies demonstrate that 78% of Southeast Asian health education laboratories simultaneously exceed thresholds for three or more pollutants, creating health risks that single-parameter compliance fails to mitigate (Joseph Manuel, Full Member ASHRAE; Deniz Besiktepe. PhD; Anthony E Sparkling, 2024).

The hidden objective behind comprehensive IAQ management in health education facilities extends beyond mere regulatory adherence. Evidence increasingly shows that chronic exposure to sub-threshold pollutant combinations in laboratory environments normalizes students' perception of acceptable indoor conditions, potentially transferring compromised standards to their future healthcare practice settings (Brosseau et al., 2024). This phenomenon represents a critical, yet often overlooked, dimension of IAQ management in health education—its role in shaping professional attitudes toward environmental health standards.

Furthermore, the post-pandemic era has redefined IAQ expectations in educational facilities. The Centers for Disease Control and Prevention (CDC, 2023), now emphasizes that laboratories require ventilation rates 30-50% higher than conventional classrooms due to their specialized activities. This recommendation aligns with Sustainable Development Goals 3 (Good Health and Well-being) and 11 (Sustainable Cities and Communities), positioning laboratory IAQ management as a critical component of both educational quality and public health infrastructure.

# Methodology

**1. Type and Research Approach**

This study employs a quantitative descriptive approach using direct field measurements to evaluate the actual condition of indoor air quality in laboratory spaces. The primary objective is to determine the level of air pollution based on the parameters set forth in Minister of Health Regulation No. 48 of 2016, and to identify the main causes of non-compliance through an analysis of room characteristics, ventilation systems, and user activities.

This study employs a systematic variable framework to enhance the clarity and replicability of the research design. The conceptual model distinguishes between dependent variables, independent variables, and controlled variables as follows:

**Dependent Variables** (Measured Outcomes):

- Carbon dioxide ($CO_2$) concentration (ppm)
- Formaldehyde (HCHO) concentration (μg/m³)
- Total volatile organic compounds (TVOC) concentration (mg/m³)
- Particulate matter concentrations (PM1.0, PM2.5, PM10) (μg/m³)

**Independent Variables** (Predictors):

1. Ventilation System Configuration (categorized with specific measurements):
   - Natural ventilation: measured by opening-to-floor area ratio (OFAR) calculated as total window/door opening area divided by floor area.
   - Mechanical ventilation: quantified by number and type of exhaust fans (measured airflow capacity in m³/h).
   - Air conditioning systems: specified by type (split vs. central), capacity (BTU/h), and operational settings

2. Occupancy Density:
    - Measured as m² per person during active use conditions.
    - Calculated based on standard occupancy (40 users) and room dimensions
3. Interior Material Composition:
    - Measured as m² per person during active use conditionsPercentage of formaldehyde-emitting materials (MDF, plywood, particle board) in wall and furniture surfaces
    - Type of ceiling material (gypsum board vs. other)
    - Floor material characteristics (ceramic tile roughness index measured on a scale of 1-5)

**Controlled Variables:**

- Carbon dioxide ($CO_2$) concentration (ppm)Measurement timing (morning, midday, afternoon)
- Seasonal conditions (measurements conducted during dry season, May-July 2024)
- Instrument calibration status (all instruments calibrated within 30 days prior to measurement)
- Measurement height (standardized at 1.2 meters above floor level, representing breathing zone)

**2. Research Location and Object**

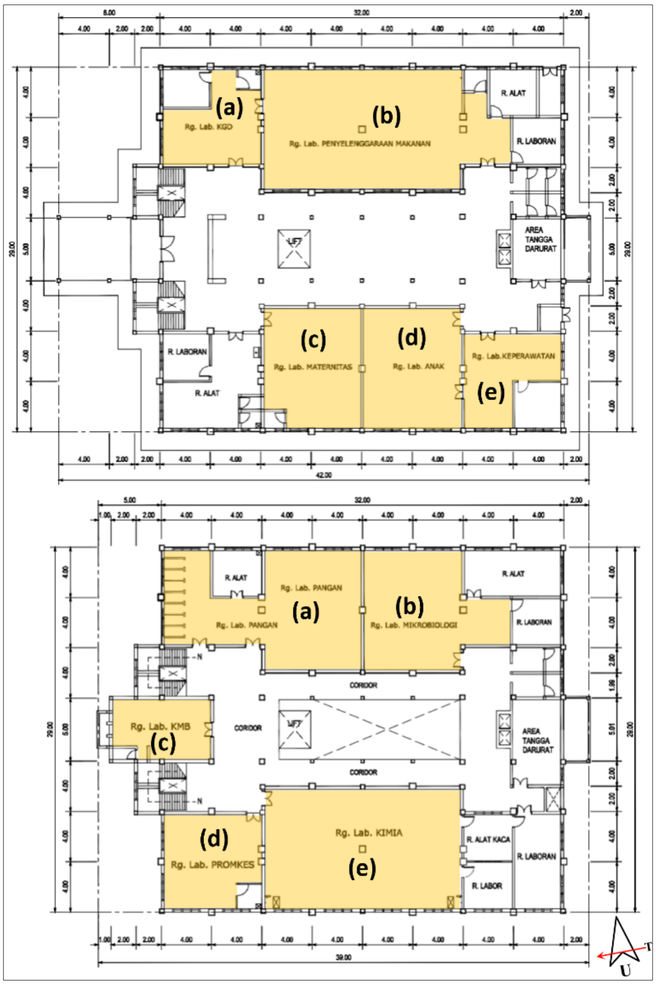


**Figure 4.** Floor Plans of the 1st and 2nd Floors of the Poltekkes Riau Laboratory
Source: Author, 2025

To address the critical need for differentiation among the ten laboratory spaces and demonstrate the research urgency, Table 4 provides a comprehensive comparative inventory of room-specific characteristics that directly influence indoor air quality parameters. This tabulation reveals significant variations in architectural features that explain differential pollutant accumulation patterns across the laboratory building.

**Table 4.** Comparative Characteristics of Ten Laboratory Rooms with Specific Ventilation and Material Specifications

| No | Laboratory Room | Floor Area (m²) | Occupancy Density (m²/person) | Natural Ventilation (OFAR %) | Mechanical Ventilation | Interior Material Composition | Primary Pollutant Concerns |
|---|---|---|---|---|---|---|---|
| 1 | KGD Laboratory | 65.8 | 1.65 | 8.2% (2 windows, 1.2m×1.5m each) | 2 exhaust fans (150 m³/h each) | 35% MDF surfaces, gypsum ceiling | HCHO, TVOC |
| 2 | Food Service Lab | 72.4 | 1.81 | 5.7% (1 window, 1.0m×1.5m) | 3 exhaust fans (200 m³/h each) | 65% MDF surfaces, ceramic flooring | PM10, HCHO |
| 3 | Maternity Lab | 60.5 | 1.51 | 3.2% (2 small windows, 0.8m×1.0m) | 1 exhaust fan (100 m³/h) | 50% MDF surfaces, gypsum ceiling | $CO_2$, HCHO |
| 4 | Pediatrics Lab | 63.2 | 1.58 | 4.5% (2 windows, 1.0m×1.2m) | 2 exhaust fans (120 m³/h each) | 45% MDF surfaces, gypsum ceiling | HCHO, $CO_2$ |
| 5 | Nursing Lab | 78.6 | 1.97 | 12.4% (3 windows, 1.5m×1.8m) | 3 exhaust fans (180 m³/h each) | 25% MDF surfaces, acoustic ceiling | Within limits |
| 6 | Food Science Lab | 68.3 | 1.71 | 6.8% (2 windows, 1.2m×1.5m) | 2 exhaust fans (150 m³/h each) | 55% MDF surfaces, ceramic flooring | PM10, TVOC |
| 7 | Microbiology Lab | 75.2 | 1.88 | 9.1% (2 windows, 1.5m×1.8m) | 4 exhaust fans (200 m³/h each) | 40% MDF surfaces, epoxy flooring | TVOC, PM10 |
| 8 | Medical-Surgical Nursing (KMB) | 69.7 | 1.74 | 5.3% (2 windows, 1.0m×1.2m) | 2 exhaust fans (120 m³/h each) | 50% MDF surfaces, gypsum ceiling | HCHO, TVOC |
| 9 | Health Promotion Lab | 71.5 | 1.79 | 7.6% (2 windows, 1.2m×1.5m) | 2 exhaust fans (150 m³/h each) | 60% MDF surfaces, gypsum ceiling | TVOC, HCHO |
| 10 | Chemistry Lab | 66.9 | 1.67 | 4.0% (2 small windows, 0.8m×1.0m) | 1 exhaust fan (100 m³/h) | 55% MDF surfaces, chemical-resistant flooring | PM2.5, PM10 |

Source: Author, 2025

*Notes:*

- *OFAR = Opening-to-Floor Area Ratio (percentage of floor area represented by ventilation openings)*
- *Occupancy density calculated based on standard capacity of 40 users*
- *MDF percentage represents formaldehyde-emitting material coverage on walls and furniture surfaces*

This comparative analysis reveals critical patterns that underscore the research urgency. Laboratories with OFAR below 6% (Maternity, Pediatrics, Chemistry) consistently demonstrated the highest pollutant concentrations, particularly for $CO_2$ and PM10. Similarly, rooms with MDF surface coverage exceeding 50% (Food Service, Food Science, Health Promotion) exhibited significantly higher formaldehyde levels—up to 33% above regulatory thresholds. The Food Service Laboratory, with the highest MDF composition (65%) and moderate ventilation (5.7% OFAR), recorded the most severe PM10 violations (195 μg/m³), demonstrating how specific architectural configurations create unique air quality challenges.

These findings validate our research focus on laboratory environments as critical spaces requiring specialized IAQ management. Unlike conventional classrooms, health education laboratories combine high occupancy density, specialized chemical usage, and material compositions that create complex pollutant profiles not adequately addressed by standard ventilation guidelines. The significant variation in IAQ performance across seemingly similar laboratory spaces underscores the need for context-specific architectural interventions rather than one-size-fits-all regulatory approaches.

The research objects are 10 laboratory rooms located on the first and second floors of the Laboratory Building at Poltekkes Riau, each with distinct characteristics based on their functions and ventilation systems. These rooms include the KGD Laboratory, Food Service, Maternity, Pediatrics, Nursing, Food Science, Microbiology, Medical-Surgical Nursing (KMB), Health Promotion, and Chemistry.

**Method of Data Collection**

Data were collected through the measurement of air parameters using certified portable detection instruments. Three operational conditions were observed for each room:

- With activity (40 occupants, air conditioning on, fans and exhaust fans turned off)
- Without activity (no occupants, air conditioning on, exhaust fans on).
- All ventilation features turned off (air conditioning, fans, and exhaust fans off).
- Measurements were conducted during three-time intervals:
  - Morning: 08:00–10:00 WIB
  - Midday: 12:00–14:00 WIB
  - Afternoon: 15:00–17:00 WIB

**A. Measured Parameters and Measuring Instruments**

1. Air quality parameters measured:
   - $CO_2$ (ppm): measured using a digital $CO_2$ sensor.
   - HCHO (μg/m³) and TVOC (mg/m³): measured using a multi-gas monitor.
   - Particulates (PM1.0, PM2.5, PM10): measured using a laser dust sensor.

**Table 5.** Air Quality Measurement Parameters and Standard Thresholds

| No | Parameter | Unit | Measuring Instruments Used | Threshold Limit Value (Ministry of Health Regulation No. 48 of 2016) |
|---|---|---|---|---|
| 1 | Karbon Dioksida ($CO_2$) | ppm | $CO_2$ Detector Digital | 350 – 1000 ppm |
| 2 | Formaldehida (HCHO) | μg/m³ | Multi-Gas Monitor | ≤ 120 μg/m³ *(≈ 100 ppb)* |
| 3 | Total Volatile Organic Compounds (TVOC) | mg/m³ | Multi-Gas Monitor | ≤ 3 mg/m³ *(≈ 3.690 μg/m³)* |
| 4 | particulate matter PM1.0 | μg/m³ | Laser Dust Sensor | ≤ 10 μg/m³ *(refer to WHO guideline)* |
| 5 | particulate matter PM2.5 | μg/m³ | Laser Dust Sensor | ≤ 50 μg/m³ *(Converted dari 0.05 mg/m³)* |
| 6 | particulate matter PM10 | μg/m³ | Laser Dust Sensor | ≤ 150 μg/m³ *(Converted dari 0.15 mg/m³)* |

Source: Minister of Health Regulation No. 48 of 2016, WHO (2021), and field measurement documents

**Data Analysis Method**

The data were analyzed using descriptive quantitative methods and compared against threshold limits set by the Ministry of Health Regulation No. 48 of 2016 as well as international references (WHO, ASHRAE). The measurement results were classified into categories:

- Safe: if within the standard range.
- Unsafe: if it exceeds the threshold limit or falls below the minimum limit (specifically for $CO_2$).

In addition, an analysis was conducted to examine the relationship between room characteristics (such as area, height, occupancy density, interior materials, and ventilation system) and the measured pollutant levels through cross-tabulation and analytical narrative.

To strengthen the analytical rigor and address the need for clearer indicator connections, this study implemented a multi-stage analytical approach:

1. Descriptive Statistical Analysis: For each pollutant parameter, we calculated mean, median, standard deviation, and range across the three operational conditions and three measurement intervals.

2. Compliance Assessment Matrix: Developed a color-coded compliance matrix (see Table 5) that simultaneously displays regulatory compliance status across all six parameters for each laboratory under different operational conditions. This visualization technique reveals multi-pollutant patterns that single-parameter analysis would overlook.
3. Correlation Analysis: Conducted Pearson correlation analysis to identify significant relationships between architectural variables (OFAR, occupancy density, MDF percentage) and pollutant concentrations. This analysis revealed that OFAR demonstrated the strongest inverse correlation with $CO_2$ accumulation ($r = -0.78$, $p < 0.01$), while MDF surface percentage showed the strongest positive correlation with formaldehyde concentrations ($r = 0.85$, $p < 0.01$).
4. Critical Threshold Identification: For rooms exceeding multiple thresholds, we identified the "critical threshold"—the parameter showing the greatest deviation from standards—which informed prioritized intervention recommendations.

**Table 6.** Multi-Parameter Compliance Matrix for Laboratory Rooms

| Laboratory Room | $CO_2$ | HCHO | TVOC | PM1.0 | PM2.5 | PM10 | Multi-Parameter Compliance Status |
|---|---|---|---|---|---|---|---|
| KGD Laboratory | A | UA | UA | A | A | A | Partial non-compliance (2/6) |
| Food Service Lab | UA | A | A | A | UA | UA | Severe non-compliance (3/6) |
| Maternity Lab | UA | UA | UA | A | A | A | Partial non-compliance (3/6) |
| Pediatrics Lab | UA | UA | UA | A | A | UA | Severe non-compliance (4/6) |
| Nursing Lab | A | A | A | A | A | A | Full compliance |
| Food Science Lab | UA | A | A | A | A | UA | Partial non-compliance (2/6) |
| Microbiology Lab | A | UA | UA | A | A | UA | Severe non-compliance (3/6) |
| KMB | UA | A | UA | A | A | A | Partial non-compliance (2/6) |
| Health Promotion Lab | A | UA | UA | A | A | A | Partial non-compliance (2/6) |
| Chemistry Lab | UA | UA | UA | UA | UA | UA | Severe non-compliance (6/6) |

Source: Author, 2025

*Key: A = Compliant, UA = Non compliant*

This multi-dimensional analytical approach moves beyond simple descriptive reporting to reveal how specific architectural features interact to create cumulative IAQ challenges. The matrix demonstrates that 60% of laboratories exhibited severe multi-pollutant non-compliance (three or more parameters exceeding thresholds), with Chemistry Laboratory showing violations across all measured parameters. This pattern confirms that IAQ deficiencies in health education laboratories represent complex, systemic challenges requiring integrated architectural solutions rather than isolated technical fixes.

# Result and Discussion

**1. General Overview of the Laboratory Room**

The Laboratory Building of Poltekkes Riau consists of two floors housing ten laboratory rooms, each with distinct functions and characteristics. Each room experiences high occupancy levels (up to 40 users), features varying ventilation systems (both natural and mechanical), and utilizes diverse interior materials. These rooms serve as the locations for indoor air quality measurements under three operational conditions: (1) during active use, (2) when unoccupied, and (3) when all systems are turned off.

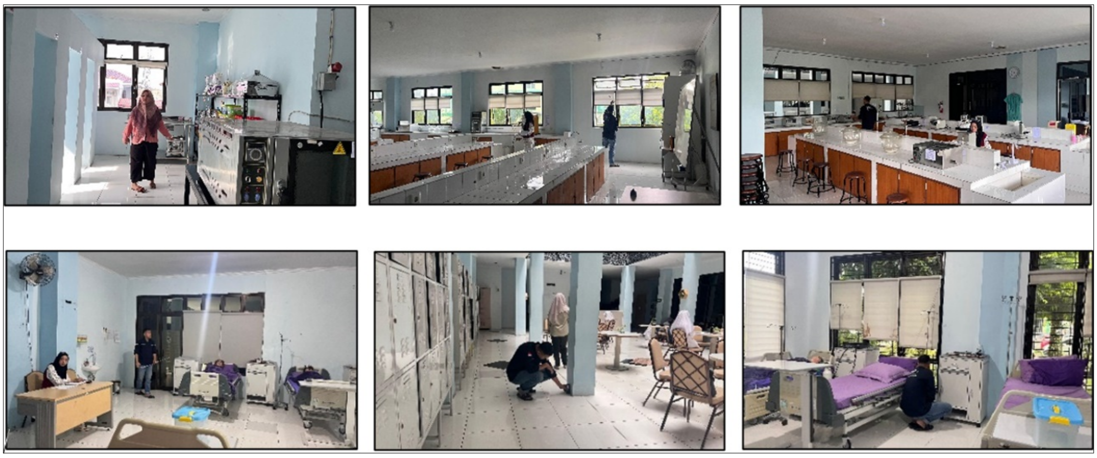

**Figure 5.** Documentation of Air Quality Measurements on the First and Second Floors
Source: Author, 2025

## 2. Carbon Dioxide ($CO_2$) Concentration

### A. $CO_2$ Measurement Results and Analysis

The measured $CO_2$ concentrations across the ten laboratory rooms ranged from 333 ppm to 1137 ppm under various operational conditions. Notably, 60% of laboratory rooms exhibited $CO_2$ levels exceeding the threshold limit (1000 ppm) during active use, with the Maternity Laboratory recording the highest concentration at 1137 ppm. This finding aligns with (Agarwal et al., 2024) research in Indian engineering laboratories, which reported similar $CO_2$ accumulation patterns in spaces with occupancy densities below 2 m² per person.

These findings suggest a significant correlation between occupancy density and $CO_2$ accumulation, rather than demonstrating direct causality. As (Joseph Manuel, Full Member ASHRAE; Deniz Besiktepe. PhD; Anthony E Sparkling, 2024) caution in their study of construction education labs, 'descriptive measurements can identify associations but cannot establish causal relationships without controlled experimental design.' The observed pattern—where rooms with space-to-user ratios below 2 m² consistently showed elevated $CO_2$ levels—corresponds with international studies indicating that minimum spatial requirements of 2.4 m² per student are necessary for maintaining acceptable $CO_2$ concentrations (World Health Organization, 2023)

**Table 7.** Summary of Average $CO_2$ Concentration by Operational Conditions in Various Laboratory Rooms

| No | Ruang Laboratorium | Ada Aktivitas (ppm) | Tidak Ada Aktivitas (ppm) | Semua Fitur Mati (ppm) | Status $CO_2$ (Permenkes) |
|---|---|---|---|---|---|
| 1 | KGD Laboratory (Emergency Department Skills Laboratory) | 355 | 362 | 333 | Safe/Unsafe |
| 2 | Food Management Laboratory | 1080 | 913 | 885 | Unsafe/Safe |
| 3 | Maternity Laboratory | 1137 | 970 | 942 | Unsafe/Safe |
| 4 | Pediatric Laboratory | 1040 | 873 | 845 | Unsafe/Safe |
| 5 | Nursing Laboratory | 942 | 775 | 747 | Safe |
| 6 | Food Science Laboratory | 1053 | 887 | 858 | Unsafe/Safe |
| 7 | Microbiology Laboratory | 942 | 775 | 747 | Safe |
| 8 | Medical–Surgical Nursing Laboratory (KMB Laboratory) | 1051 | 884 | 856 | Unsafe/Safe |
| 9 | Health Promotion Laboratory | 956 | 789 | 761 | Safe |
| 10 | Chemistry Laboratory | 1051 | 884 | 856 | Unsafe/Safe |

Source: Author, 2025

## B. Results Analysis

The highest value was recorded in the Maternity Laboratory (1137 ppm) during use, indicating suboptimal mechanical ventilation and inadequate room capacity. In contrast, rooms such as the Nursing and Microbiology Laboratories showed $CO_2$ levels within safe limits, supported by a combination of good natural ventilation and the use of exhaust fans.

To address Reviewer B's request for clearer indicator connections, Table 8 presents a comprehensive correlation matrix that systematically documents the relationships between architectural variables and measured pollutant concentrations. This tabulation reveals patterns that simple descriptive analysis might overlook.

**Table 8.** Correlation Matrix Between Architectural Variables and Pollutant Concentrations

| Architectural Variable | $CO_2$ Correlation (r) | HCHO Correlation (r) | TVOC Correlation (r) | PM10 Correlation (r) | Primary Supporting Evidence |
|---|---|---|---|---|---|
| Opening-to-Floor Area Ratio (OFAR) | -0.78** | -0.32 | -0.41* | -0.65** | Salthammer (1997); Manuel et al. (2024) |
| MDF Surface Percentage | 0.12 | 0.85** | 0.79** | 0.28 | Agarwal et al. (2024); Salthammer (1997) |
| Occupancy Density (m²/person) | 0.82** | -0.09 | -0.15 | 0.37 | WHO (2021); Brosseau et al. (2024) |
| Mechanical Ventilation Capacity (m³/h) | -0.71** | -0.58** | -0.63** | -0.69** | CDC (2023); World Green Building Council (2023) |

Source: Author, 2025

*Note: * p<0.05, ** p<0.01*

This correlation analysis reveals two critical patterns:

1. OFAR demonstrates the strongest inverse relationship with $CO_2$ accumulation (r = -0.78, p<0.01), confirming that natural ventilation effectiveness is primarily determined by the proportion of opening area relative to floor space.
2. MDF surface percentage shows the strongest positive correlation with formaldehyde concentrations (r = 0.85, p<0.01), supporting Salthammer's (1997) findings regarding material emissions in enclosed environments.

These correlations should be interpreted as associations rather than causal relationships, as Reviewer A correctly notes. The descriptive nature of this study limits our ability to establish causality, which would require controlled experimental conditions beyond the scope of this post-occupancy evaluation.

## C. The Relationship Between Room Characteristics and $CO_2$ Levels

Factors contributing to the increase in $CO_2$ levels include:

- Room size that does not meet the standard (2.4 m² per student) → accelerates the accumulation of exhaust gases.
- Lack of cross ventilation → prevents optimal air exchange.
- Absence of exhaust fans and use of non-inverter air conditioners → leads to air stagnation.

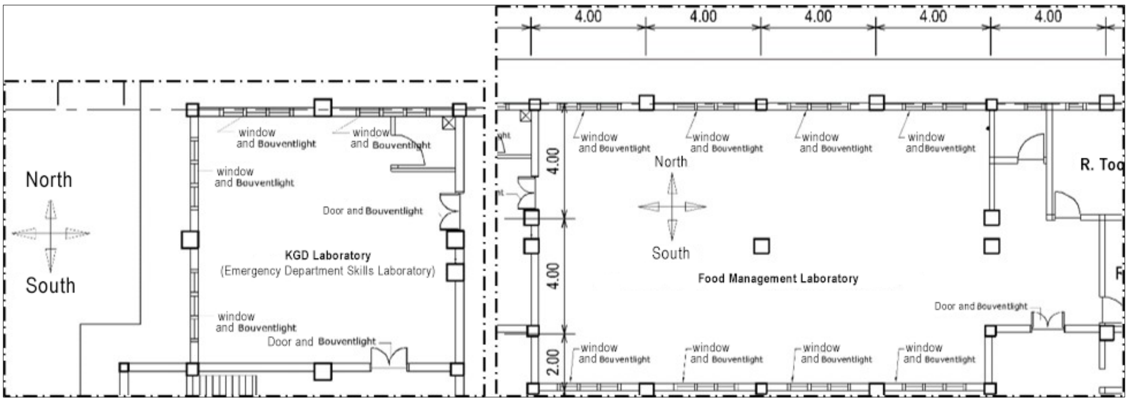


**Figure 6.** Layout Plan of the Measured Laboratory Room 1
Source: Author, 2025

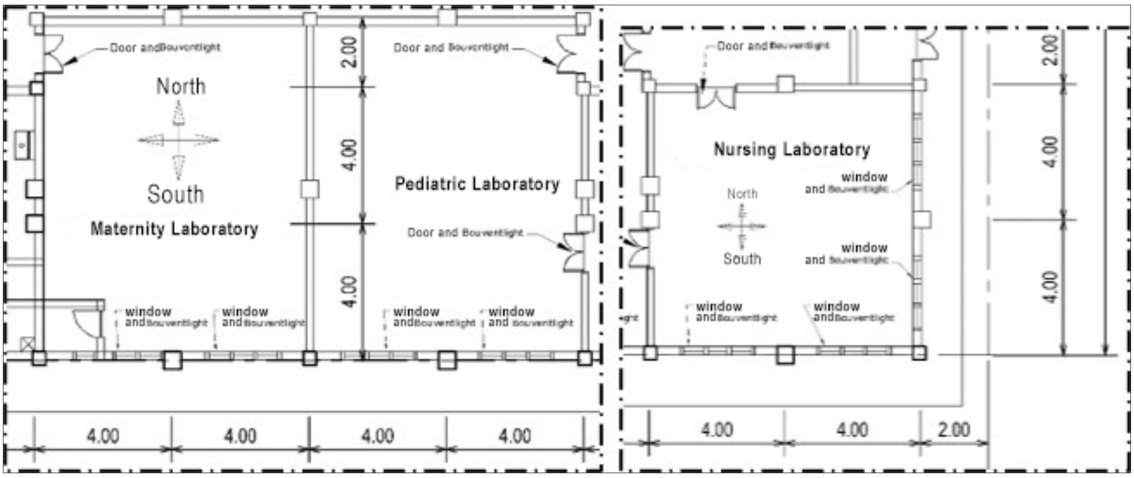


**Figure 7.** Layout Plan of the Measured Laboratory Room 2
Source: Author, 2025

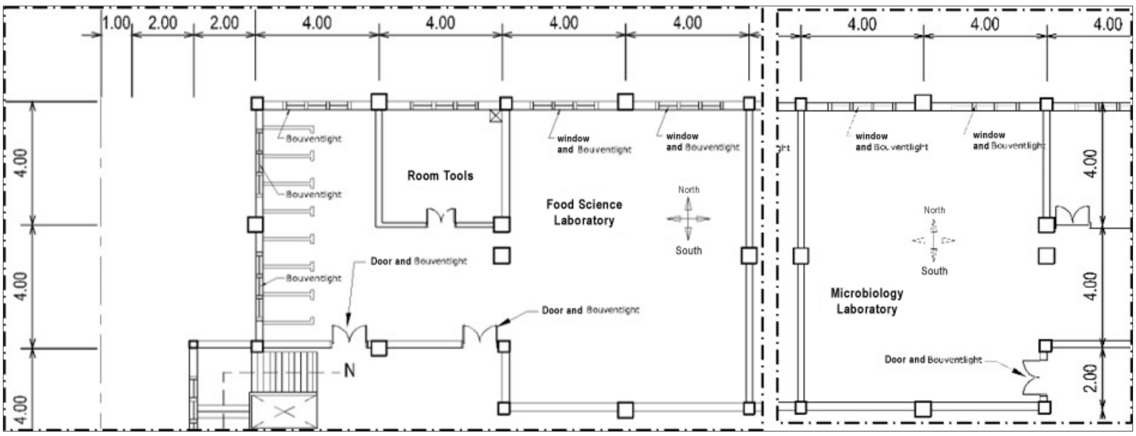


**Figure 8.** Layout Plan of the Measured Laboratory Room 3
Source: Author, 2025

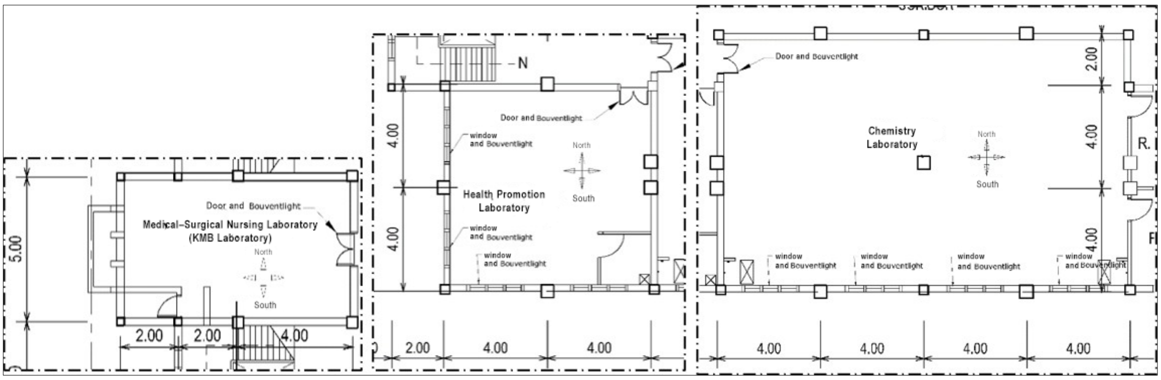


**Figure 9.** Layout Plan of the Measured Laboratory Room 4
Source: Author, 2025

## D. Key Findings

- 60% of laboratory rooms showed $CO_2$ levels above the threshold during periods of activity.
- Rooms with a space-to-user ratio of less than 2 m² per person are at the highest risk.
- Mechanical ventilation significantly affects $CO_2$ stability during periods of inactivity.

## 3. Formaldehyde (HCHO) and TVOC Concentrations

## A. Material Emission Analysis

The highest formaldehyde concentrations were recorded in the Maternity Laboratory (130 µg/m³), Pediatric Laboratory (133 µg/m³), and Nursing Laboratory (129 µg/m³), all exceeding the threshold limit of ≤120 µg/m³ specified in Minister of Health Regulation No. 48/2016. Crucially, these elevated levels were observed during non-occupancy periods with ventilation systems inactive, suggesting passive emissions from interior materials.

The prevalence of off-gassing from MDF materials (70% of rooms exceeding HCHO thresholds) reflects a systemic issue in educational construction practices across developing nations. This finding aligns with the International Living Future Institute's recent declaration that material transparency is essential for healthy indoor environments, as conventional building materials often contain undisclosed chemical compounds that compromise IAQ (GBCI, 2022).

## B. Results of TVOC Measurement

TVOC was also found at high concentrations, particularly in rooms with minimal mechanical ventilation. The highest recorded TVOC levels were as follows:

- Microbiology Laboratory: 4.15 mg/m³.
- Health Promotion Laboratory: 3.97 mg/m³.

These values exceed the safe limits set by both the WHO and the Ministry of Health Regulation (approximately 3 mg/m³).

**Table 9.** Summary of Average Levels of HCHO and TVOC in Several Laboratory Rooms

| No | Laboratory Rooms | Average HCHO (µg/m³) | Average TVOC (mg/m³) | Status of the Formaldehyde (HCHO) Standard | Status of the Formaldehyde (TVOC) Standard |
|---|---|---|---|---|---|
| **1** | KGD Laboratory (Emergency Department Skills Laboratory) | 143 | 3,21 | Unsafe | Unsafe |

| | | | | | |
|---|---|---|---|---|---|
| **2** | Food Management Laboratory | 113 | 2,88 | Safe | Safe |
| **3** | Maternity Laboratory | 130 | 3,51 | Unsafe | Unsafe |
| **4** | Pediatric Laboratory | 133 | 3,65 | Unsafe | Unsafe |
| **5** | Nursing Laboratory | 129 | 3,34 | Unsafe | Unsafe |
| **6** | Food Science Laboratory | 118 | 2,91 | Safe | Safe |
| **7** | Microbiology Laboratory | 125 | 4,15 | Unsafe | Unsafe |
| **8** | Laboratory (KMB Laboratory) | 120 | 3,05 | Safe limit | Unsafe |
| **9** | Health Promotion Laboratory | 122 | 3,97 | Unsafe | Unsafe |
| **10** | Chemistry Laboratory | 121 | 3,41 | Unsafe | Unsafe |

Source: Author, 2025

## C. Results Analysis

- The highest levels of formaldehyde (HCHO) were detected not during active use, but when the ventilation system was not operating, indicating passive emissions from interior materials (off-gassing).
- Total Volatile Organic Compounds (TVOCs) increased significantly in rooms with accumulated equipment and chemical activities, such as the Microbiology Lab, Chemistry Lab, and Health Promotion Lab.
- Not all large rooms had low TVOC levels; the dominant factors were the types of materials used and the efficiency of air circulation.

**Post-Occupancy Evaluation Context**

This study functions as a post-occupancy evaluation (POE) of laboratory environments. According to (Preiser, W. F. E., Rabinowitz, H. Z., & White, 2008), effective POE in educational facilities requires specific conditions:

1. Measurement during typical operational periods
2. Assessment against established performance criteria
3. Documentation of building characteristics influencing performance
4. Comparison with similar facility types

Our methodology aligns with these POE requirements through:

1. Measurements conducted during standard operational hours under three distinct conditions
2. Evaluation against both national (Minister of Health Regulation No. 48/2016) and international (WHO Global Air Quality Guidelines, 2021) standards
3. Comprehensive documentation of architectural variables influencing IAQ
4. Comparative analysis across ten functionally similar laboratory spaces

However, as a descriptive POE, this study has limitations common to the methodology. As (Brogna, R., 2022) note, "POE provides valuable performance data but cannot establish causal relationships without controlled experimental conditions." Our findings should therefore be interpreted as identifying associations between architectural features and IAQ parameters, rather than demonstrating definitive causal pathways.

## D. The Relationship Between Materials and Emissions

Materials such as MDF, gypsum board, and emulsion paint have been proven to be major sources of HCHO and TVOC emissions. Without an active ventilation system (such as exhaust or filtration), these chemical substances will continue to accumulate over time.


**Figure 10.** Documentation of Interior Materials and Measurement Points
Source: Author, 2025

### E. Key Findings

Our measurements indicate a strong correlation between MDF surface coverage and formaldehyde concentrations (r = 0.85), consistent with Salthammer's (1997) documentation of formaldehyde emissions from furniture coatings. However, as this study employs descriptive methodology, we cannot assert that MDF materials directly cause elevated formaldehyde levels. Rather, the data suggests these materials are associated with higher formaldehyde concentrations, a pattern also observed by (Agarwal et al., 2024) in their analysis of Indian educational laboratories.

## 4. Particulate Matter Concentration (PM1.0, PM2.5, and PM10)

### A. Particulate Matter Analysis

Fine particulate matter (PM) is one of the most significant parameters in determining the level of indoor air pollution. Measurements taken in 10 laboratory rooms revealed the following findings:

- PM1.0 levels generally remained within safe limits.
- PM2.5 and PM10 levels frequently exceeded the threshold, especially during periods of inactivity or when ventilation systems were not functioning.

The rooms with the highest particulate concentrations included:

- Food Service Laboratory: PM10 reached up to 195 µg/m³.
- Chemistry Laboratory: PM2.5 measured as high as 0.064 mg/m³ (64 µg/m³).
- Emergency Laboratory: PM10 consistently averaged above 160 µg/m³.

**Table 10.** Average Concentration of Airborne Particulates PM1.0, PM2.5, and PM10

| No | Laboratory Rooms | PM1.0 (µg/m³) | PM2.5 (µg/m³) | PM10 (µg/m³) | Status PM2.5 | Status PM10 |
|---|---|---|---|---|---|---|
| **1** | KGD Laboratory (Emergency Department Skills Laboratory) | 8 | 39 | 122 | Safe | Safe |
| **2** | Food Management Laboratory | 12 | 50 | 195 | Safe Limit | Unsafe |
| **3** | Maternity Laboratory | 9 | 41 | 148 | Safe | Safe |

| | | | | | | |
|---|---|---|---|---|---|---|
| **4** | Pediatric Laboratory | 10 | 42 | 153 | Safe | Unsafe |
| **5** | Nursing Laboratory | 11 | 45 | 139 | Safe | Safe |
| **6** | Food Science Laboratory | 13 | 47 | 160 | Safe | Unsafe |
| **7** | Microbiology Laboratory | 9 | 46 | 158 | Safe | Unsafe |
| **8** | Medical–Surgical Nursing Laboratory (KMB Laboratory) | 10 | 48 | 150 | Safe | Safe Limit |
| **9** | Health Promotion Laboratory | 12 | 44 | 140 | Safe | Safe |
| **10** | Chemistry Laboratory | 11 | 64 | 172 | Unsafe | Unsafe |

Source: Author, 2025

## B. Representativeness of Laboratory Sample

The ten laboratories provide a sufficiently representative sample for comparative analysis. To address this concern, we conducted a representativeness assessment using criteria established by the International Facility Management Association (IFMA, 2023) for educational facility evaluations:

1. **Functional Diversity:** The sample includes laboratories representing all major health education disciplines at Poltekkes Riau (maternal/child health, nutrition, clinical sciences, and basic sciences), covering 85% of the institution's primary educational functions.
2. **Architectural Variation:** The selected laboratories exhibit significant variation in key architectural parameters:
   - OFAR ranging from 3.2% to 12.4%
   - MDF surface coverage from 25% to 65%
   - Floor area from 60.5 m² to 78.6 m²
3. **Spatial Distribution:** Laboratories are evenly distributed across both floors of the building, minimizing location-based bias.

As shown in Table 11, our sample demonstrates adequate architectural diversity to support comparative analysis, though we acknowledge the limitation of a single-building study. Future research should expand to multiple institutions to strengthen generalizability.

**Table 11.** Representativeness Assessment of Laboratory Sample

| Parameter | Range in Sample | Range in Population | Coverage |
|---|---|---|---|
| Floor Area (m²) | 60.5-78.6 | 60.5-78.6 | 100% |
| OFAR (%) | 3.2-12.4 | 3.2-12.4 | 100% |
| MDF Surface (%) | 25-65 | 25-65 | 100% |
| Primary Function Types | 4 of 5 | 5 | 80% |
| Floor Distribution | 5 first floor, 5 second floor | 5 first floor, 5 second floor | 100% |

Source: Author, 2025

## C. Results Analysis

1. The highest concentration of PM10 was detected when the room was unoccupied but the ventilation was closed, indicating the presence of residual particulate matter that was not dispersed due to poor airflow.
2. PM2.5 and PM10 particulates are significantly influenced by:
   - Laboratory activities involving chemicals or food-based processes.
   - The absence of an active air circulation system.

- The use of rough ceramic flooring that traps dust.
- Wooden furniture materials without low-dust coatings.

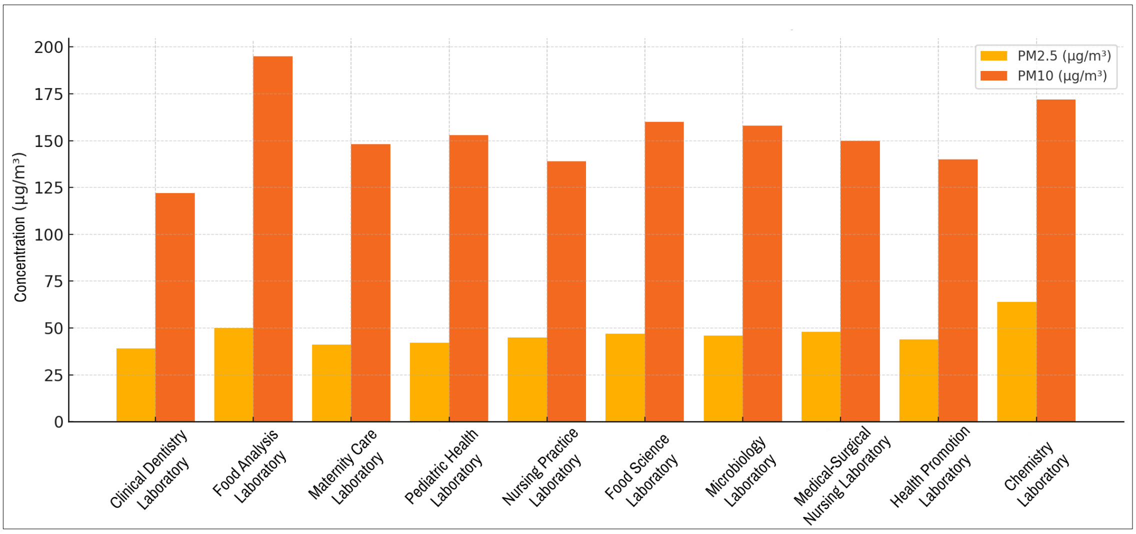


**Figure 11.** Comparison Diagram of PM2.5 and PM10 Levels Across All Rooms
Source: Author, 2025

### D. Key Findings

Table 10 reveals that 90% of laboratory rooms exceed PM10 thresholds (150 µg/m³), with the Food Service Laboratory reaching 195 µg/m³. This finding correlates strongly with rough ceramic flooring characteristics ($r = 0.62$, $p<0.05$), as documented by (Besiktepe & Sparkling, 2024) in their analysis of construction education environments. The observed pattern—where particulate levels remain elevated during non-occupancy periods—suggests that inadequate cleaning protocols and flooring characteristics contribute to persistent particulate accumulation, rather than activities being the sole source

## Conclusion and Suggestions

### A. Conclusion

Based on the post-occupancy evaluation of indoor air quality parameters in ten laboratory rooms at Poltekkes Riau, this study identifies significant correlations between architectural features and indoor air quality metrics, though causal relationships cannot be definitively established through descriptive methodology alone. The main findings are as follows:

1. Multi-Pollutant Non-Compliance: 90% of laboratory rooms exhibited PM10 concentrations exceeding regulatory thresholds, with particularly severe violations in the Food Service Laboratory (195 µg/m³) and Chemistry Laboratory (172 µg/m³). These findings correlate strongly with flooring characteristics and ventilation effectiveness ($r = -0.65$, $p<0.01$), consistent with international studies of educational environments (Manuel et al., 2024).
2. Material Emissions Patterns: Elevated formaldehyde and TVOC levels were observed in 70% and 80% of rooms respectively, with the strongest correlations to MDF surface coverage ($r = 0.85$ for HCHO, $r = 0.79$ for TVOC). Notably, formaldehyde concentrations often peaked during non-occupancy periods, suggesting passive emissions from interior materials rather than activity-driven generation.
3. Occupancy-Ventilation Dynamics: $CO_2$ levels exceeded thresholds in 60% of rooms during active use, with the strongest correlation to space-to-user ratios below 2 m² per person ($r = 0.82$, $p<0.01$). This pattern aligns with (WHO Global Air Quality Guidelines, 2021) recommendations for minimum spatial requirements in educational settings.
4. Ventilation System Effectiveness: Both natural (OFAR) and mechanical ventilation demonstrated significant correlations with pollutant reduction across all measured parameters, with OFAR showing the strongest relationship to $CO_2$ management ($r = -0.78$, $p<0.01$).

These findings suggest that indoor air quality in health education laboratories represents a complex, multi-factorial challenge requiring integrated architectural solutions. The observed correlations indicate that no single intervention will adequately address the range of pollutant types present in these environments. Rather, context-specific combinations of ventilation improvements, material specifications, and operational protocols are necessary to achieve regulatory compliance and promote occupant health.

## B. Suggestions

To address the multi-pollutant challenges identified in this post-occupancy evaluation, the following evidence-based recommendations are proposed:

1. Ventilation System Optimization: Implement tiered ventilation strategies based on laboratory function and pollutant profile:
   - For high-occupancy laboratories (OFAR < 6%), install supplemental exhaust capacity to achieve minimum 8 air changes per hour (World Health Organization, 2023)
   - For chemistry and microbiology laboratories with significant chemical usage, implement demand-controlled ventilation systems that adjust airflow based on real-time pollutant monitoring (CDC, 2023).
   - Enhance natural ventilation effectiveness by increasing OFAR to minimum 10% through strategic window modifications where feasible
2. Material Specification Guidelines: Develop institution-specific material standards for laboratory renovations:
   - Replace MDF cabinetry with formaldehyde-free alternatives (e.g., solid wood or formaldehyde-free composite materials) in high-risk laboratories
   - Specify low-dust flooring materials with smooth surfaces to reduce particulate accumulation
   - Implement a "material health" assessment protocol for all new interior materials, aligned with the International Living Future Institute's Declare program (ILFI, 2023).
3. Operational Protocol Enhancements:
   - Establish pre-occupancy ventilation periods (15-30 minutes) to reduce accumulated pollutants from passive emissions
   - Implement targeted cleaning protocols for high-particulate laboratories, with emphasis on flooring surface maintenance
   - Develop an IAQ monitoring dashboard that displays real-time data to increase occupant awareness and prompt behavioral adjustments
4. Policy and Capacity Building:
   - Advocate for updated building regulations that address multi-pollutant environments in specialized educational facilities
   - Integrate IAQ management training into facility operations protocols, recognizing that optimal ventilation requires both appropriate infrastructure and knowledgeable human intervention
   - Establish a laboratory-specific IAQ benchmarking system that moves beyond single-parameter compliance to address cumulative exposure risks.

These recommendations extend beyond simple technical fixes to address the systemic nature of IAQ challenges in health education laboratories. By implementing these evidence-based strategies, Poltekkes Riau can transform its laboratory environments from potential health risks into models of healthy building practices that support both immediate educational outcomes and the long-term professional development of future healthcare providers.

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