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Original Research

INTEGRATED INDOOR AIR QUALITY PROTOCOL FOR AN ADDITIVE MANUFACTURING WORKSHOP: CASE STUDY OF FABLAB PRESIDENT UNIVERSITY

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ABSTRACT

Integrated Indoor Air Quality Protocol for an Additive Manufacturing Workshop: Case Study of FabLab President University. *The indoor air quality (IAQ) issues in 3D Printing Workshop arise from high equipment usage, material handling, and continuous student presence. 3D printing process generates pollutants that may threaten health and safety. Due to Indonesia's currently lacks a specific national standard for IAQ specifically in 3D Printing Workshop, creating a regulatory gap for these educational facilities. This study conducted a regulatory inventory to identify applicable standards for IAQ in the 3D Printing Workshop at President University. Two national regulations were included as part of this inventory: Permenkes No. 2 Tahun 2023 and Permenaker No. 5 Tahun 2018 as primary sources. Regulations were selected based on legal authority, parameter coverage, relevance to workshop activities, and strictness of threshold limits to support a comprehensive and health-protective assessment approach. Eight key IAQ parameters were identified: temperature, relative humidity, Air Velocity, noise level, PM10, PM2.5, total suspended particles (TSP), and volatile organic compound (VOC). These reflect thermal comfort, contamination, physical hazards, and chemical pollutants from 3D printing processes and human occupancy. The study proposes a systematic IAQ parameter framework integrating standard measurement techniques as a conceptual reference for environmental monitoring, regulatory compliance, occupational health and safety (OSH) practices, and higher education accreditation requirements.*

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INTRODUCTION

The technology of three-dimensional printing has undergone a significant rise and is one of the elements that bring a new face to the manufacturing industry [1]. Its advantages in customization, rapid prototyping, and cost efficiency have made it increasingly accessible for academic and research purposes. The increasing availability and affordability of additive manufacturing equipment have encouraged higher education institutions to integrate 3D printing facilities into their learning environments to support both research development and practical skill-building among students. [2]. It is an undeniable fact that the technology of 3D printing is in great demand today particularly because of the high precision and accuracy involved in the construction of complex structures.

The 3D printing workshop examined in this study is located at President University, Jababeka, an area characterized by intensive industrial activities [3]. The university uses its additive manufacturing facilities as part of its educational system because it supports both research development and practical testing and prototype creation [4]. The student experience benefits from these facilities because they develop technological skills which prepare students for future employment. The industrial setting surrounding the campus may contribute to background air pollutant levels, which can influence indoor air quality within campus facilities. The campus area requires hazard identification together with essential IAQ parameter assessment to maintain a secure and healthy educational atmosphere [5].

Though there are several benefits of 3D printing, health should be considered as one of the main drawbacks of the technology [6]. One of the main steps in the printing process is the application of heat to polymer-based materials, which normally leads to the emission of particulate matter and gases into the atmosphere around the printer [7]. Such emissions in the form of fine and ultrafine particles together with VOCs, may very well impact adversely human health especially to the lungs in case the people are working in poorly ventilated indoor places where exposure is somewhat higher [8].

The accreditation assessment guidelines for engineering study programs under LAM Teknik Regulation No. 6 Year 2025 require institutions to demonstrate commitment to occupational health, safety, and environmental (OSH) standards. This includes demonstrating regulatory compliance, providing OSH supporting facilities, documenting OSH practices, and conducting regular OSH evaluations. The absence of dedicated IAQ standards for 3D printing facilities creates difficulties for universities seeking to fulfill these accreditation requirements through appropriate environmental monitoring frameworks [13].

This study aims to develop a conceptual and regulatory-based IAQ parameter framework specifically designed for additive manufacturing workshop environments in higher education institutions. Using regulatory inventory, IPOC analysis, and parameter mapping, it identifies important IAQ factors relevant to workshop activities and local laws. The proposed framework is intended to serve as a conceptual reference for environmental monitoring, OSH practice development, and regulatory compliance in educational fabrication laboratory settings, and may provide a replicable model for other universities operating similar additive manufacturing facilities.

MATERIALS AND RESEARCH METHODS

Figure 1 illustrates the research framework of this study [14]. This study employs a conceptual and regulatory-based research approach aimed at developing an integrated IAQ parameter framework for additive manufacturing workshop environments. Rather than conducting direct IAQ measurements or empirical exposure assessments, this study focuses on hazard identification, regulatory mapping, and systematic parameter selection as the primary methodological components.

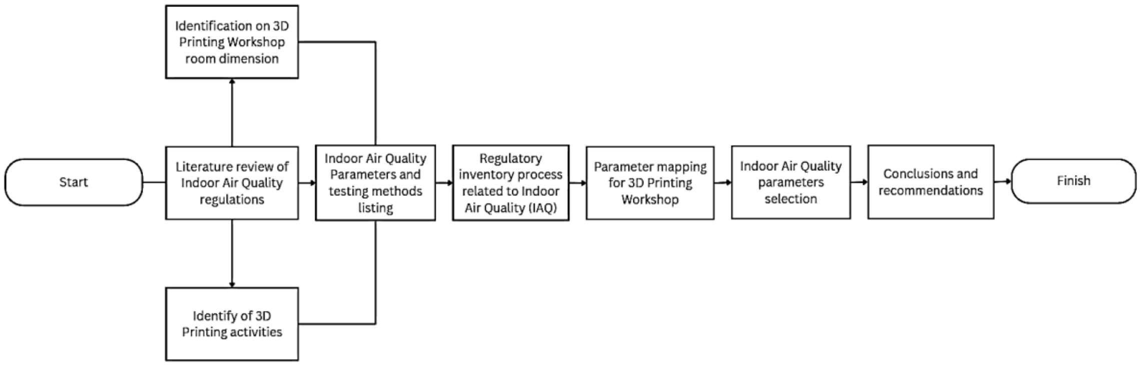

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Figure 1. Research Framework

The study began with a preliminary characterization of the 3D printing workshop at President University, including room dimensions, equipment inventory, and operational activities, conducted through direct observation as a basis for contextual framework development. This was followed by a literature review of national indoor air quality regulations relevant to workshop environments, and a systematic parameter selection process based on the results of risk factor mapping associated with 3D printing activities. Identified regulations were then compiled into a regulatory inventory table, which can be seen in Table 4. This study did a screening process on each regulation to determine its applicability to the 3D Printing Workshop environment and its activities in the location. The inventory provided the base information which the research team use for their regulatory mapping process and their selection of specific parameters. Parameter mapping was carried out to systematically identify and consider all relevant parameters required for assessment in the 3D printing workshop. This study was conducted at the 3D Printing Workshop of President University. The room dimension was measured using the laser meter.

RESEARCH RESULTS AND DISCUSSION

Based on the room layout in Figure 2 and the dimensions shown in the 3D Printing Workshop plan, with the length of 10.893 m and the width of 15.822 m with height of 3.449 m which make the total room volume is approximately 594.9 m^3. The 3D printing workshop space operates as both a 3D printing facility and a workspace which contains eight 3D printers and ten workstation tables that are used at various times. The workshop structure consists of reinforced concrete columns, while the wall partitions are finished with plywood panels, which creates a continuous non-porous surface that meets the requirements of technical laboratory spaces. The materials provide structural strength, but the enclosed concrete walls together with the sealed flooring system create barriers which impede air movement and control the spread of pollutants throughout the space. The workshop's indoor air quality assessment requires evaluation of the spatial design and building materials and complete building size because these factors determine how well pollutants will be diluted and how effectively air will circulate through the space.

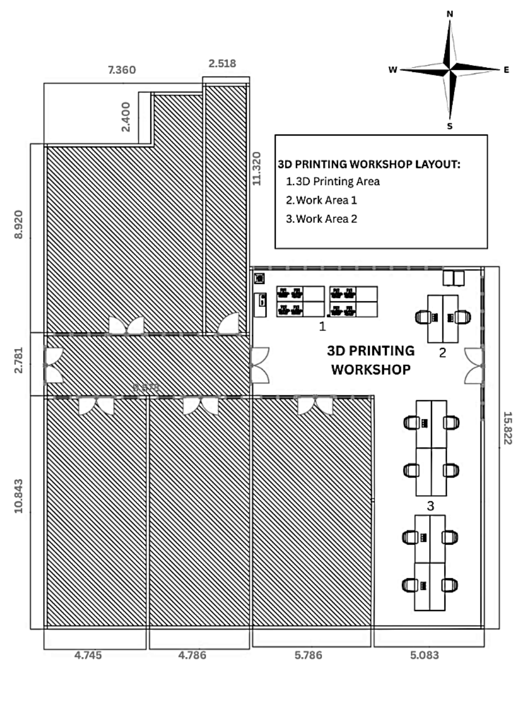

Figure 2. Room Layout

The HVAC key parameters for the 3D Printing Workshop are summarized in Table 1. The 3D Printing Workshop is equipped with a cassette-type air conditioning system with a cooling capacity of 5 PK, which is installed at the centre of the room to provide thermal comfort and support air circulation. The HVAC system operates primarily to regulate indoor air temperature and relative humidity, ensuring a comfortable working environment during laboratory activities. Air distribution is delivered through ceiling-mounted diffusers, allowing conditioned air to be supplied evenly across the workspace.

The system functions mainly as an air recirculation system, as it does not include a dedicated outdoor air intake or mechanical exhaust for pollutant removal. As a result, the effectiveness of the HVAC system in maintaining indoor air quality relies on its ability to circulate indoor air and dilute airborne contaminants generated during the operation of 3D printing equipment. Key HVAC performance parameters considered in this study include air temperature, relative humidity, air velocity, and air change rate (ACH), which are essential for evaluating thermal comfort and air distribution within the workshop.

Table 1. HVAC Parameters

HVAC		
NO	**SOURCES**	**DESCRIPTION**
A	**HEAT LOAD**	
1	Number of occupant(s)	Total occupant using the room per day: 12 - 15 people
2	Machine	3D Print machine type: FDM Printers: - X1 CARBON (350 - 1000 W) - BAMBU LAB (300 - 800 W) - CREALITY CR-10 V2 (500 - 800 W) - CREALITY CR-10 V3 (500 -800 W) - CREALITY CR-10 MINI (300 - 500 W) - CREALITY CR-X (600 - 1000 W) - ANET A8 PLUS (400 - 600 W) SLA/MSLA Printer: - ELEGOO SATURN RESIN PRINTER (120 - 300 W) Heat released: FDM Printers: - X1 CARBON → $1.26 \times 10^6 – 3.60 \times 10^6$ J/h - BAMBU LAB → $1.08 \times 10^6 – 2.88 \times 10^6$ J/h - CREALITY CR-10 V2 → $1.80 \times 10^6 – 2.88 \times 10^6$ J/h - CREALITY CR-10 V3 → $1.80 \times 10^6 – 2.88 \times 10^6$ J/h -CREALITY CR-10 MINI → $1.08 \times 10^6 – 1.80 \times 10^6$ J/h -CREALITY CR-X → $2.16 \times 10^6 – 3.60 \times 10^6$ J/h -ANET A8 PLUS → $1.44 \times 10^6 – 2.16 \times 10^6$ J/h SLA/MSLA Printer: - ELEGOO SATURN RESIN PRINTER → $4.32 \times 10^5 – 1.08 \times 10^6$ J/h
3	Lamp	Lamp power: 72 W Lamp numbers: 12 TL Fluorescent lamp Heat released: 3.11×10^6 J/h
4	Sun radiation	Windows numbers: 4
B	**VENTILATION**	
1	Air supply location	The source of air: AC 3.449 m on top of the machine
2	Air outlet location	Air outlet: AC Distance between the machine: 3.449 m on top of the machine
C	**AIR CONDITIONING**	
1	Air conditioning system	Type: Daikin Cassette Air Conditioner 5 PK Air change rate: 3.5 ACH
2	Cooling capacity	Number of AC(s): 1 Power: 42,600 BTU/h

The energy consumed by 3D printers is directly related to the heat released into the working environment. For the machines used in this study (Table 1), the heat release was estimated using the standard formula:

$$Q = P \times t$$

Where Q is the heat released (J), P is the printer power rating (W), and t is the operating time (h). The resulting heat output ranges from 1.08×10^6 to 3.60×10^6 J/h for FDM printers and 4.32×10^5 to 1.08×10^6 J/h for SLA/MSLA printers, providing a practical basis for assessing thermal load in the workshop.

Air changes per hour (ACH) is defined as the volume of air introduced or exhausted per hour divided by the total room volume which shows how often a space undergoes complete air replacement. This parameter is essential in HVAC design because it directly links airflow capacity with thermal comfort and contaminant control [15]. The total internal heat load of this study consists of the heat output from three-dimensional printers plus the metabolic heat generated by twelve to fifteen workshop occupants. The researchers established a target ACH of 3.5 by comparing their total heat load with the ventilation airflow, which they measured as Q, and the room volume, which they measured as V. The formula is stated as below:

$$ACH = Q \ / \ V \ (Maxi\ Calculator\ 2026)$$

Maintaining this ACH serves two essential functions: regulating thermal comfort and controlling indoor air quality. A work environment becomes healthier when proper ventilation systems function to dilute airborne pollutants which include FDM printer particulate matter and resin-based SLA/MSLA printer volatile organic compounds. The design of HVAC systems should follow established procedures because it enables organizations to achieve two goals: they can manage their room temperatures and maintain suitable indoor air quality which benefits both their employees and their equipment operations.

The IPOC analysis for the 3D Printing Workshop is summarized in Table 2. The Input–Process–Output-Customer (IPOC) analysis was applied to systematically identify potential sources of indoor air quality concerns in the 3D Printing Workshop. The main users of the space who operate the 3D printing facilities for their academic and research work and their prototyping activities make up the Customer element of the system. The selected users of the study face direct contact with all emissions and thermal loads and noise which machines produce during their operational phase and after their processing phase. The customer element of the IPOC structure shows that staff and students need IAQ assessment because it affects both their educational environment and their health. The inputs in the workshop include electrical energy, 3D printing materials, and the operation of printing equipment. The processes consist of equipment operation, monitoring activities, and supporting tasks conducted during the printing process. These activities may lead to several undesired outputs, such as airborne particulate matter, gaseous emissions, and heat accumulation within the indoor environment. The control measures considered in this analysis include the existing air conditioning system, room layout arrangement, and operational practices implemented in the workshop.

This IPOC framework provides a structured basis for understanding the relationship between workshop activities and potential indoor air quality impacts. By identifying the inputs, processes, and undesired outputs, the IPOC analysis supports the selection of critical indoor air quality parameters and assists in evaluating the adequacy of existing control measures in maintaining acceptable indoor environmental conditions.

Table 2. IPOC Analysis

NO	ACTIVITY	INPUT: MATERIAL	INPUT: EQUIPMENT	PROCESS	OUTPUT: DESIRE	OUTPUT: UNDESIRED
1	Material preparation for 3D printing	PLA Filament	Filament spool, dry box	Preparation of filament by loading it into the 3D printer. Filament may be dried beforehand to reduce moisture content and prevent printing defects	Filament ready to be printed	**Associated IAQ Aspects:** - None **Solid and Material Waste Aspects:** - Plastic packaging waste - Damaged filament - Unused filament pieces
2	Heating & melting filament	Thermoplastic filament	3D printer hot end, heating element	Filament is heated in the hot end to reach melting temperature	Moulted filament	**Associated IAQ Aspects:** - Heat - PM_{10} - $PM_{2,5}$ - VOC **Solid and Material Waste Aspects:** - Degraded filament residue inside nozzle - Burnt plastic residue - Failed heating components
3	Printing process	Molten thermoplastic filament	3D printer	Layer-by-layer extrusion of molten filament through a nozzle according to sliced 3D model to form the desired object	Printed object according to design	**Associated IAQ Aspects:** - Noise - Heat - PM_{10} - $PM_{2,5}$ - VOC **Solid and Material Waste Aspects:** - Failed prints - Plastic waste from unsuccessful prints - Support structure waste - Excess filament strings and blobs
4	Cooling	Printed thermoplastic layers	Air conditioner	Printed layers are cooled using fans or ambient air to solidify material and maintain dimensional stability	Stable and dimensionally accurate printed object	**Associated IAQ Aspects:** - Air Velocity - $PM_{2,5}$ **Solid and Material Waste Aspects:** - Dimensional defects - Warped or cracked printed parts
5	Finishing	Printed object	Hand tools	Manual removal of support structures and surface finishing to improve final appearance and functionality	Finished 3D printed product	**Associated IAQ Aspects:** - Noise - Relative Humidity - PM_{10} - $PM_{2,5}$ - TSP **Solid and Material Waste Aspects:** - Plastic dust waste - Removed supported materials - Defective finished products - Hand-tool contaminated waste (plastic residue)
6	Material preparation for resin 3D printer	Liquid photopolymer resin	Resin bottle, resin vat, spatula	Liquid resin is poured into the resin vat prior to printing	Resin ready to be printed	**Associated IAQ Aspects:** - VOC **Solid and Material Waste Aspects:** - Spilled liquid resin - Contaminated containers and tools - Resin packaging waste

UNIT PROCESS						
NO	ACTIVITY	INPUT		PROCESS	OUTPUT	
		MATERIAL	EQUIPMENT		DESIRE	UNDESIRED
7	Printing process	Liquid photopolymer resin	Resin 3D printer	UV light selectively cures resin layer-by-layer through an LCD mask based on the sliced 3D model	Printed object according to design	**IAQ Aspects:** - Heat - Noise - VOC **Solid and Material Waste Aspects:** - Failed resin prints - Excess uncured resin - Contaminated resin vat residue
8	Part removal	Printed resin object	Scraper, gloves	Printed object is removed from build plate	Printed part safely removed	**Associated IAQ Aspects:** - VOC **Solid and Material Waste Aspects:** - Resin contaminated wipes and gloves - Damaged printed parts - Solid resin waste
9	Post-curing	Clean resin object	UV curing chamber	Printed object is further cured under UV light to complete polymerization	Fully cured printed object	**Associated IAQ Aspects:** - Heat - VOC **Solid and Material Waste Aspects:** - Overcured or deformed printed objects - UV-damaged rejected products
10	Maintenance activity	Lubricant, filament residue, resin residue, dust	3D printer, hand tools, replacement parts	Inspection of 3D printers, part replacement, nozzle maintenance, troubleshooting, and functional testing	Properly functioning equipment, reduced machine failure, extended equipment lifetime	**Associated IAQ Aspects:** - Noise - PM_{10} - $PM_{2,5}$ - TSP - VOC **Solid and Material Waste Aspects:** - Used spare parts - Resin or filament contaminated maintenance waste - Electronic waste from damaged components
11	Cleaning	Cleaning agents (detergent, alcohol), dust, filament residue, resin spills	Cleaning tools (cloth, mop, vacuum cleaner), waste containers	Cleaning printer surfaces, workstations, and floors; removal of filament and resin residues; waste collection	Clean and organized laboratory environment, reduced contaminant accumulation	**IAQ Aspects:** - PM_{10} - $PM_{2,5}$ - VOC - Total Bacteria Count **Solid and Material Waste Aspects:** - Mixed solid waste (plastic, dust, resin caps) - Contaminated cleaning cloth and mops - Chemical waste from cleaning agents

Table 3 below presents the matrix of relationship between each unit process in 3D printing and its potential impact on IAQ parameters. The table demonstrates essential emission points which pollutants released through each 3D printing process. This structured approach enables researchers to identify which processes at their laboratory work site cause the most severe negative effects on IAQ while developing methods to reduce these effects and demonstrating why workplaces like 3D printing workshop needs to measure environmental conditions during additive manufacturing.

Table 3. Identification Matrix of Unit Process vs. Potential IAQ Parameters

UNIT PROCESS / PARAMETER	MATERIAL PREPARATION FOR 3D PRINTING	HEATING & MELTING FILAMENT	PRINTING PROCESS	COOLING	FINISHING	MATERIAL PREPARATION FOR RESIN 3D PRINTING	PRINTING PROCESS	PART REMOVAL	POST-CURING	MAINTENANCE ACTIVITY	CLEANING ACTIVITY	HUMAN CONTRIBUTION	REFERENCE
TEMPERATURE		✓	✓				✓		✓			✓	16–22
RELATIVE HUMIDITY					✓							✓	18,21,22
AIR VELOCITY				✓									23
LIGHT												✓	
NOISE			✓		✓		✓						24,25
PM10		✓	✓		✓					✓	✓		18,19,23,26
PM2,5		✓	✓	✓	✓					✓	✓		18,19,23,26,27
TOTAL SUSPENDED PARTICLES					✓					✓		✓	6
VOLATILE ORGANIC COMPOUND		✓	✓			✓	✓	✓	✓	✓	✓		6,16,18,19,23,26, 28
CARBON DIOXIDE												✓	29
TOTAL BACTERIA COUNT												✓	30

The reviewed literature shows that Table 3 identification matrix correctly displays how unit processes in the 3D Printing Workshop connect with their corresponding IAQ parameters. This finding indicates that IAQ risks in additive manufacturing workshops are systemic in nature, spanning multiple operational stages, which underscores the importance of comprehensive parameter identification as a foundation for future empirical monitoring.

Based on the IPOC and parameter matrix analysis, VOC was identified as the parameter with the most extensive process coverage, appearing across material preparation, active printing, post-curing, and cleaning stages. This suggests that VOC represents a priority hazard parameter in both polymer-based and resin-based additive manufacturing environments, warranting particular attention in future empirical IAQ monitoring.

The previous research established that VOC emissions from thermoplastic extrusion and resin curing operations produce noticeable indoor odors because many VOC substances emit odors at very low concentrations. The context establishes that odor functions as a sensory demonstration of VOC emissions instead of representing an individual pollutant measurement [28].

The final critical parameter table excluded odor because the selected regulatory framework did not provide a precise national regulatory threshold that could be quantitatively measured. The study determines its main research focus on measurable research elements which researchers can compare to existing national testing standards.

The evaluation process involved two essential criteria which tested how strictly regulations-controlled laboratory operations.

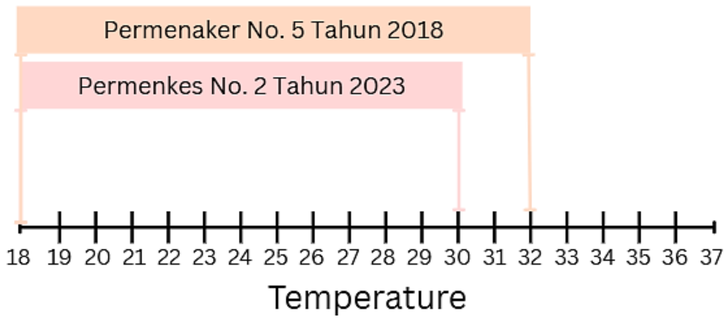

Figure 3. Illustration for Parameter Selection

The regulatory inventory process was conducted through a systematic search and screening of applicable Indonesian national regulations related to IAQ, occupational health, and environmental standards. The search was carried out using official government regulatory databases to ensure document validity and legal authority. From this process, three principal regulations were identified as relevant references: Permenaker No. 5 Tahun 2018, Permenkes No. 2 Tahun 2023, and Permenkes No. 48 Tahun 2016. Each regulation was carefully reviewed and compiled into a regulatory inventory table containing key information, including issuing authority, year of enactment, scope of application, regulated parameters, and corresponding threshold limit values.

A review of regulatory scope indicated that Permenkes No. 48 Tahun 2016 is specifically intended for office workplaces and administrative environments. Since the 3D Printing Workshop functions as a technical laboratory with operational processes involving thermoplastic extrusion, resin handling, and equipment-generated heat, its environmental characteristics differ substantially from typical office settings. Therefore, Permenkes No. 48 Tahun 2016 was not included in the subsequent parameter selection stage.

The evaluation subsequently focused on Permenaker No. 5 Tahun 2018 and Permenkes No. 2 Tahun 2023 to assess their relative strictness and contextual suitability for the 3D Printing Workshop. This regulatory inventory formed the basis for the structured mapping and selection process presented in Table 4, where each parameter was assessed according to regulatory strictness, workspace relevance, and legal authority.

The temperature limits established by Permenkes No. 2 Tahun 2023 and Permenaker No. 5 Tahun 2018 provide a regulatory framework to evaluate their relative strictness and applicability to the 3D Printing Workshop. Permenkes No. 2 Tahun 2023 specifies an indoor temperature range of 18–30°C, reflecting a comfort-based standard intended for general indoor environments. In contrast, Permenaker No. 5 Tahun 2018 permits temperatures up to 32°C, as it emphasizes occupational heat tolerance rather than indoor thermal comfort. While the workshop requires adequate thermal control due to heat-generating equipment, operational conditions may demand greater flexibility than strict comfort-based standards, making the comparison between these two regulations relevant for contextual evaluation.

Table 4 presents the regulatory inventory. The study used Table 3 to find operational parameters which directly connect to the workshop's activities. The selected parameters include temperature, relative humidity, Air Velocity, noise, PM_{10}, $PM_{2.5}$, TSP, and VOC. The research team evaluated every parameter according to national standards to identify the most suitable reference points which would support assessment and regulatory compliance in future IAQ monitoring activities at the 3D Printing Workshop.

Table 4. Inventory of Regulations and Selected Parameters

NO	PARAMETER	QUALITY STANDARD	UNIT	REGULATIONS	CONSIDERATION / REASON	SELECTED REGULATION	SELECTED QUALITY STANDARD	UNIT	STANDARD METHOD
1	TEMPERATURE	18 - 30	°C	Permenkes No. 2 Tahun 2023	Indoor thermal comfort standard (18–30°C) suitable for enclosed laboratory environments with continuous occupancy.	Permenkes No. 2 Tahun 2023	18 - 30	°C	ISO 7726
		≤32		Permenaker No. 5 Tahun 2018					
2	RELATIVE HUMIDITY	40 - 60	% Rh	Permenkes No. 2 Tahun 2023	Occupational humidity control (40–60% RH) supports operational stability and worker exposure management in technical activities.	Permenaker No. 5 Tahun 2023	40 - 60	% Rh	ISO 7726
		40 - 60		Permenaker No. 5 Tahun					
3	AIR VELOCITY	0,15 - 0,25	m/s	Permenkes No. 2 Tahun 2023	Controlled indoor airflow range (0.15–0.25 m/s) ensures pollutant dispersion while maintaining occupant comfort.	Permenkes No. 2 Tahun 2023	0,15 - 0,25	m/s	ISO 7726
4	NOISE	≤60	dBA	Permenkes No. 2 Tahun 2023	Indoor acoustic limit (85 dBA) appropriate for academic laboratory settings and prolonged learning activities.	Permenaker No. 5 Tahun 2018	≤85	dBA	SNI 7231:2009
		≤85		Permenaker No. 5 Tahun 2018					
5	PM_{10}	≤70	μg/m^3	Permenkes No. 2 Tahun 2023	Strict indoor particulate limit (70 μg/m^3) aligned with IAQ-based respiratory protection.	Permenkes No. 2 Tahun 2023	≤70	μg/m^3	SNI 7119.3:2005
		≤180		Permenaker No. 5 Tahun 2018					
6	$PM_{2,5}$	≤25	μg/m^3	Permenkes No. 2 Tahun 2023	Health-based fine particle limit (25 μg/m^3) relevant to emissions from thermoplastic extrusion processes.	Permenkes No. 2 Tahun 2023	≤25	μg/m^3	SNI 7119.14:2016
7	TOTAL SUSPENDED PARTICLES	≤230	μg/m^3	Permenkes No. 2 Tahun 2023	Indoor suspended particle control (10 μg/m^3) suitable for material handling and workshop activities.	Permenaker No.5/2018	≤10	μg/m^3	SNI 7119.3:2017
		≤10		Permenaker No.5/2018					
8	VOLATILE ORGANIC COMPOUND	≤3	ppm	Permenkes No. 2 Tahun 2023	Comprehensive indoor VOC limit (3 ppm) applicable to chemical emissions from printing and post-processing.	Permenkes No. 2 Tahun 2023	≤3	ppm	ISO 16000-6

A total of eight IAQ parameters were selected for monitoring in the 3D Printing Workshop, covering thermal comfort, biological, physical, and chemical aspects. These include temperature, relative humidity, air velocity, noise, PM_{10}, $PM_{2,5}$, TSP, and VOC. Each parameter was evaluated against Permenaker No. 5 Tahun 2018 and Permenkes No. 2 Tahun 2023 based on regulatory strictness, relevance to laboratory activities, and legal authority. This regulatory inventory formed the basis for subsequent mapping and selection, ensuring each parameter aligns with occupational health and laboratory safety requirements.
The regulatory inventory identified three principal regulations as relevant references: Permenkes No. 2 Tahun 2023, Permenaker No. 5 Tahun 2018, and Permenkes No. 48 Tahun 2016. Permenkes No. 48 Tahun 2016 was excluded from parameter selection as its scope is explicitly limited to office and administrative environments, which differ substantially from the operational characteristics of an additive manufacturing workshop. The remaining two regulations were evaluated comparatively based on regulatory strictness, legal authority, and contextual applicability to the 3D printing workshop environment.
Permenkes No. 2 Tahun 2023 reflects a health-protective orientation with stricter threshold values suitable for enclosed educational spaces with continuous occupancy, while Permenaker No. 5 Tahun 2018 provides occupational exposure limits oriented toward worker tolerance during productive work hours. Rather than adopting a single regulatory reference, each parameter was evaluated individually to determine the most contextually appropriate standard. Temperature, air velocity, PM_{10}, $PM_{2.5}$, and VOC were referenced under Permenkes No. 2 Tahun 2023 due to their health-based indoor air quality significance. Relative humidity and TSP were referenced under Permenaker No. 5 Tahun 2018 as these standards are equally applicable to workshop operational conditions. Noise was referenced under Permenaker No. 5 Tahun 2018 with a threshold of ≤85 dBA, as the stricter limit of 65 dBA under Permenkes No. 2 Tahun 2023 was considered less applicable given the mechanical nature of 3D printing operations which inherently generate equipment-driven noise levels exceeding comfort-based indoor standards.
All selected parameters were aligned with standardized measurement methods based on SNI and ISO, forming a proposed systematic IAQ parameter framework as presented in Table 4, intended as a conceptual reference for future empirical monitoring activities.

CONCLUSIONS AND RECOMMENDATIONS

This study proposed a conceptual IAQ parameter framework intended to guide indoor air quality assessment in additive manufacturing workshop environments at higher education institutions, using the 3D Printing Workshop at President University as a case study.
Eight key IAQ parameters were identified through room characterization, HVAC analysis, IPOC mapping, operational process assessment, and regulatory inventory. The parameters include temperature, relative humidity, air velocity, noise, PM_{10}, $PM_{2.5}$, total suspended particles (TSP), and volatile organic compounds (VOC).
Based on the IPOC and parameter matrix analysis, VOCs and fine particulate matter ($PM_{2.5}$ and PM_{10}) were identified as priority hazard parameters due to their extensive process coverage across thermal degradation and resin curing activities. The IPOC mapping confirmed that IAQ risks are systemic across multiple operational stages rather than isolated to a single process.
This study developed an integrated regulatory reference by selecting the most contextually appropriate threshold values from Permenkes No. 2 Tahun 2023 and Permenaker No. 5 Tahun 2018 for each identified parameter. The absence of a dedicated Indonesian regulation specifically addressing IAQ in educational technical workshop environments highlights a regulatory gap that warrants attention in future policy development. The proposed framework is intended to support environmental monitoring, OSH practice development, and regulatory compliance in educational fabrication laboratory settings, and may serve as a replicable model for other universities operating similar additive manufacturing facilities.

Although the proposed framework provides a structured basis for IAQ assessment, its practical applicability should be validated through field measurements and empirical exposure assessment in future studies.

ETHICAL APPROVAL

This study did not require formal ethical approval as it did not involve human subjects or sensitive personal data. The research was conducted through direct observation of the workplace environment.

CONFLICT OF INTEREST

The authors declare no conflict of interest

AUTHOR CONTRIBUTIONS

ALM, YBSM: supervision and critical review of the manuscript; ALM: data analysis; YBSM: manuscript writing; ALM: data collection and documentation;. All authors read and approved the final manuscript.

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