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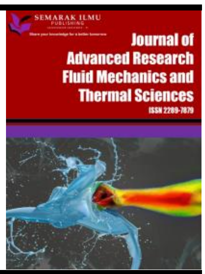

Engineering Laboratory IAQ Monitoring: A Real-Time Solution using Raspberry PI and Grafana Dashboard

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ABSTRACT

The World Health Organization (WHO) has reported that people who spent approximately 80 % - 90 % of their time being indoors daily, resulted in over 3 million premature deaths each year due to a disease caused by indoor air pollution. High concentration of indoor air pollutant such as particulate matter, carbon dioxide and imbalances between temperature and relative humidity have the potential to create unpleasant odour and dusty air, resulting in an incommodious environment and respiratory issues. The purpose of this project was to investigate the air quality at two engineering laboratories in a higher learning institution. A survey revealed that 41 % of students reported a bad odour in the workshop laboratory, while 38 % experienced the same issue in the Material & Automation Laboratory of the particular institution. Therefore, an IAQ (Indoor Air Quality) alert system was developed. The system consisted of sensors that measured the air quality, whereby data were continuously read and fed into a Raspberry PI controller by using a wireless communication device namely ESP-32. The controller has a smart card memory for logging purposes. The data were continuously read by a computer dashboard by using Grafana software. A beacon light was integrated with the controller to provide an alert indicator. Parameters measured were Particulate matter concentration, Carbon Dioxide level, Temperature and Humidity level. Measurement was done for three days while students were undergoing their activities in both laboratories. Data was benchmark with IAQ DOSH (Department of Safety & Health) and WHO (World Health Organisation). It was found that Particulate Matter in both laboratory and Workshop exceeded the IAQ limits, while the Carbon Dioxide reading was a concern. Temperature and Humidity were at acceptable levels but required constant monitoring.

1. Introduction

The term “indoor air quality (IAQ)” refers to the air quality inside of a space within a constructed building. It can be detrimental to human health, well-being, and comfort as they relax or work inside buildings such as homes, offices, laboratories, and other workplaces [1]. Since COVID 19 pandemic,

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the importance of maintaining good indoor air quality had raised significant worldwide concern due to unseen pollutants. This may bring negative impact on human health because each human breathes m^3 of air and spend a substantial fraction of time in buildings every day, which is estimated to be 80 % - 90%, Al Madhoun *et al.,* [2]. On the other hand, particularly vulnerable population groups may be more susceptible to the effects of indoor air pollution due to various reasons, including health conditions, or age status [3].

Indoor environments, especially in workplaces and laboratories contain complex mixtures of pollutants in mid-air which can affect occupants' health and safety. These include particulate matters (PM_{10}, $PM_{2.5}$), volatile organic compounds (VOCs), ozone (O_3), carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), micro-organisms and others biological contaminants. If occupants are exposure longer to air pollutants, it may lead to many health issues comprising eye irritation, fatigue, headaches, and dizziness. Also, it may lead to more serious consequences, such as asthma, respiratory infections, allergies responses, lung cancer, and other chronic problems.

According to a report published in PNAS by Lelieveld *et al.,* [4], an estimate of 8.8 million death toll was attributable to indoor and outdoor air pollution each year. Indoor air pollutants can be derived from various sources such as volatile organic contaminants that can be released from various building materials, including paint, thinner, pesticides, furniture, and cleaning products. Furthermore, pollutants like particulate matters (PM), carbon dioxide (CO_2), carbon monoxide (CO) and nitrogen dioxide (NO_2) can be released from combustion of fuel, gas, and tobacco smoke. Besides, micro-organisms such as moulds and fungi are easily grown in humid and warm environments, whereby they can release spores and cause biological contamination in air, as taken from previous studies [5,6]. Additionally, ozone (O_3) is a strong oxidising agent which can be released in a few ways including through air purifiers by-products as well as copiers and printers during operations [7].

Indoor air temperature and humidity also plays a crucial role in maintaining healthy indoor air quality. Norazman *et al.,* [8] conducted a study in determining the performance of indoor environment quality in education facilities in particular determining the environmental comfort for learning. It was concluded that for a sustainable thermal comfort, the temperature would be at 27˚ C, humidity at 40 % and air flow velocity to be at 0.30 m/s. Although these parameters only served as guidelines, the possibility in sustaining such readings can be influenced by learning locations having inadequate ventilations, and if it is in laboratories, equipment operations, intensive practical work undertaken and the existence of poor exhaust system. Generally, high humidity and temperature can cause discomfort to occupants because body sweat cannot evaporate efficiently. However, in serious cases, it can cause heat stroke, skin problems, eye problems, respiratory problems, as well as hyperthermia. Conversely, low humidity and low temperature can cause dry eyes, respiratory problems, and hypothermia. High humidity and low temperature can cause heat exhaustion and provide an ideal grow condition for mould, mildew micro-organisms while low humidity and high temperature can cause dry skin. It was also concluded that temperature and humidity levels that exceed or below a certain benchmark may influence and reduce occupants' cognitive performance such as having difficulty to concentrate on tasks or activities [9].

School of Engineering students at University of Wollongong in Malaysia often conduct practical experiments and replication processes in the engineering workshops and laboratories. Particularly in UOWM laboratories, the absence of a proper ventilation system around the closed room laboratory area may lead to accumulation of pollutants such as high concentrations of carbon dioxide. Inside the laboratories unfavorable temperature and humidity conditions occur, especially when closed for prolonged durations.

Poor indoor air quality index could bring health issues to those who are working in the laboratories or workshops including mild nausea, dizziness, fatigue, headaches, nose congestion and other common respiratory health symptoms.

The aim of this project is to investigate the trend of UOWM laboratories and workshop indoor air quality to verify the relation between temperature and relative humidity by using an existing air quality meter. An indoor air quality controller with data acquisition system was developed to measure temperature, relative humidity, particulate matters, and carbon dioxide. The sensory controlled based system will be able to conclude the air quality level inside the laboratories and display it through Graphic User Interface (GUI) interfacing with beacon light to indicate the air quality level.

1.1 Importance of Study

The indoor air quality at Engineering Laboratories and workshops in learning institutions has not been given much attention since research is mostly focused on office spaces, classrooms, other commercial buildings, and residential homes. Laboratories and workshops are critical locations in learning institutions because plenty of equipment and machinery are housed and used by students for experimental works and activities such as soldering, welding, cutting, milling, and drilling. Depending on the size of laboratory areas to accommodate the number of students, it can be a problem when there is poor ventilation due to overcrowding.

Architectural designs and construction of buildings, especially school buildings and institutions may tend to overlook this by only focusing on the entire block construction. When apportioning constructed blocks into laboratories and workshops, the importance of having ventilation systems, air flow exhausts, viaducts installations, windows, emergency exits should be considered and importantly the type of laboratory. Type of laboratory refers to Chemical, Electrical, Mechanical and Material laboratories. Workshops and laboratories may have their own safety criteria and are environmentally conducive for students to undergo activities comfortably.

Based on standards stated by ASHRAE [10], an ideal environment for comfort is to have the indoor humidity and temperature levels maintained in the range of 40 % - 70 % and 20 °C - 26 °C, respectively. Therefore, a proper indoor air ventilation system is crucial to mitigate air contamination that contains particulate matter (PM2.5 and PM10). Particulate matter can be potentially emanated into air resulting from anthropogenic activities and waste productions through equipment operations. An indoor air quality investigation was done in eight laboratories located in University Kebangsaan Malaysia (UKM). The measurements recorded were benchmarked with ASHRAE standards. It was found that only one laboratory recorded an average high reading on particulate matter. This was attributed to intensive practical research being carried out, thus concluding that using an air purifier in conjunction with ventilated fresh outdoor air can lower indoor air pollution, Hosnon *et al.,* [11]. However, it still relies, though, on how the laboratory is designed, namely how many apertures are there to allow air to circulate and having the necessity of a ventilated exhaust system being installed.

Mitigating indoor air pollutants, particularly PM2.5 and PM10, is very important. An exhaust ventilated system may immediately remove contaminated air while simultaneously letting in fresh air can be able to sustain the indoor air particulate matter within its limits. Nevertheless, it is also subjected to number of occupancies at one time including types of activities carried out intensively.

The results of air quality investigations conducted in a specific institutional laboratory prompted air quality investigation in other institution with a diverse laboratory environment in other institutions.

1.2 Problem Statement

The School of Engineering students at University of Wollongong Malaysia often conduct classes, experiments, machinery works and replication processes in engineering workshops and laboratories. However, due to the absence of a proper ventilation system around in a closed room laboratory area, it may lead to the accumulation of pollutants inside laboratories such as high concentrations of carbon dioxide. When closed for prolonged durations, it may cause unfavourable temperature and humidity conditions. A poor indoor air quality index could bring about health issues to workers in laboratories or workshops such as mild nausea, dizziness, fatigue, headaches, nose congestion and other common respiratory health symptoms.

A survey that was conducted on student experience at engineering laboratories, revealed that 41% of respondents experienced heavy odours and dusty smells in the Materials and Automation laboratory, 38% of respondents indicated strong odours in the Engineering Workshop, and 21% of respondents reported that heavy odours were inhaled in Electrical and Electronic system laboratory (Figure 1).

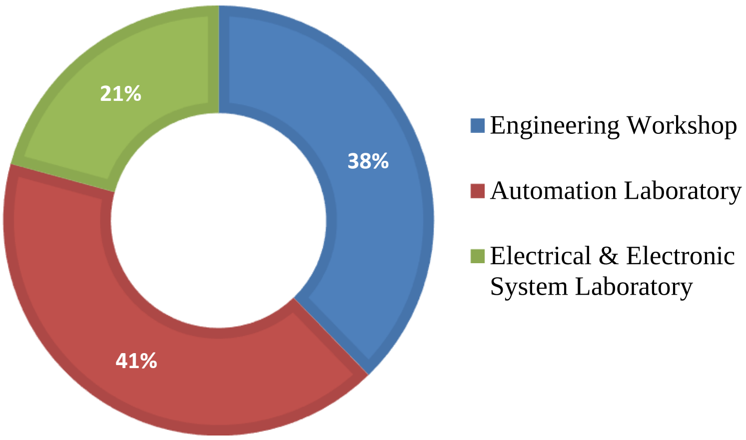

Fig. 1. Percentage of students who experienced strong odours in selected laboratories

Based on the survey results, there was a need to address the poor indoor air quality problem at these selected laboratories. Focus was to investigate into air quality at both Material and Automation laboratory as well as Engineering Workshop. Parameters involved in measurement were temperature, relative humidity, particulate matters and carbon dioxide. The unstable parameter readings in such locations were investigated by developing an IAQ alert systems through the applications of environmental sensors. They were a Raspberry PI controller which have a memory card for data acquisition and Grafana Dashboard as a graphical user interface (GUI) for data display and monitoring.

Furthermore, this proposed IAQ alert system that were used as open source IoT based SCADA was concluded to be a low cost measuring data in real-time, which effectively able to monitor critical parameters. Additionally, such system was proposed to counter the existing IoT health meters that were expensive, limited capability and other constrained settings [12]. The second objective was to evaluate the parameters of temperature, humidity, particulate matter (PM2.5 and PM10) and carbon dioxide by benchmarking these findings with IAQ guidelines that was established by the Department of Occupational Health and Safety (DOSH).

1.3 Literature Review
1.3.1 Sources of indoor air pollutant

Indoor air pollutants refer to the existence of harmful substances that are at high concentration levels and circulate inside buildings, including particulate matter ($PM_{2.5}$), carbon dioxide (CO_2), volatile organic compound (VOCs), and other biological contaminants. These substances can bring about negative impacts on human body. It has been mentioned that indoor air quality is significantly influenced by a few factors. Firstly, is the outdoor air quality in Malaysia. The world's air quality index for 2022 reported by IQAir [13] disclosed that Malaysia had an annual average of 2.5 microns particulate matter in the air. Klang, Petaling Jaya and Kuala Lumpur had experienced an average particulate matter concentration level of 27.1 μg/m^3, 26.5 μg/m^3 and 17.6 μg/m^3, respectively, in 2022. It was noticeable that the air quality in Klang and Petaling Jaya fell under the "unhealthy" range while Kuala Lumpur was slightly better which fell "under unhealthy for sensitive groups" range.

It is recognised that outdoor contaminant concentrations and building airtightness have a great impact on IAQ because high levels of outdoor pollutant concentrations increase the chances for the pollutants to seep into indoor environments via ventilation [14].

In addition, PM Air Quality Guidelines (AGQs) has been revised and new air quality guidelines and standards for particulate matters ($PM_{2.5}$ & PM_{10}) were released by International Health Agency, WHO [15]. This was to provide a nationwide government of airborne pollutants control legal policy in order to protect public health. AQGs for $PM_{2.5}$ stipulated by WHO recommend that the 24-hour averaging time should not exceed 15 μg/m^3 and annual averaging time legal limit is set at 5 μg/m^3. Meanwhile, PM_{10} should not exceed 45 μg/m^3 legal limit at 24-hour averaging time and annual averaging mean is limited at 15 μg/m^3.

In Malaysia, $PM_{2.5}$ concentration level for some cities in Malaysia has exceeded the legal limit of 5 μg/m^3 annual mean. Primary standards are to provide public health protection to health sensitive groups, including children, the elderly, asthmatics, and chronic obstructive pulmonary disease (COPD). Secondary standards are to provide public welfare protection, such as damage to crops, animals, buildings and decrease in visibility. Both WHO and EPA (Environment Protect Agency, US) [16], have set different PM guidelines, hence it was observed that the EPAs' particulate matter limit is higher than limit set by WHO. However, comparing it with 2022 annual $PM_{2.5}$ in KL, Klang and Petaling Jaya still exceeded the limit but according to the 24-hour average, most days are below the limit point.

Human activities within buildings significantly impact indoor air quality. Daily tasks can emit waste gases, tobacco smoke, cleaning agents, pesticides, dust, mould, allergens, and fibers. Additionally, cooking, fuel combustion, and the use of machinery for material cutting release carbon dioxide (CO_2), particulate matter (PM) and other chemical substances into the indoor environment.

Construction materials, paints, aerosol sprays, raw materials, heavy oil, biomass, manufacturing machinery, equipment, furniture, and office electronics are also sources of volatile organic compounds (VOCs) and ozone (O_3) pollutants. Kim *et al.,* [17] summarised the health effects of VOCs and other pollutants released by human activities. Beyond particulate matter and CO_2, many VOCs are key components of materials used in workplace facilities, including interior furnishings, machinery, equipment, tools, heavy oil, cleaners, sprays, and pesticides [18]. Therefore, exposure to volatile organic compounds (VOCs) has been the main suspect factor in causing many asthmas and asthmatic symptoms [19].

Particulate matter has an adverse effect on human respiratory system. It contains solid particles that are combined with liquid droplets suspended in air. Sources of emission are from dust, anthropogenic activities, such as industrial emissions, deforestation and construction activities.

Particulate matter (PM) also comes in many sizes, but PM_{10} and $PM_{2.5}$ are regulated by world-wide nation as well as WHO because both sizes are associated with greatest proportion of adverse health risks. In terms of penetrability, the smaller the particulate matter the deeper it can penetrate within the respiratory tract, starting from nasal passageway down to alveoli, taken from previous study by Kim *et al.,* [20]. Several epidemiological studies show that long-term exposure to fine particulate matter of 10 µm to 2.5 µm, which can lead to cardiovascular, respiratory and coronary heart disease leading to reduce in life expectancy. While short-term exposure could cause various health impacts including increases in human respiratory and cardiovascular hospital admission for chronic obstructive pulmonary disease (COPD) and asthma due to fine particle like $PM_{2.5}$ can easily penetrate through respiratory airway and deposited in lungs thereby aggravate asthma and COPD as taken from previous studies [21-23]. Han *et al.,* [24] in a previous separate study done had analysed that the pre-school asthma, and COPD patients were more vulnerable to PM-related hospitalisation admission. Therefore, maintaining a low level of particulate matter (PM) pollutant within the stipulated standard is crucial to ensure human health and safety.

Carbon Dioxide (CO_2) is an odourless and colourless gas that can be produced through human activities or is naturally occurring at surrounding environments, which include burning of fossil fuels for electricity and transportation, as well as human respiration processes. Several studies indicated that a small amount of carbon dioxide (CO_2) is harmless to human. However, high concentration of CO_2 may threaten human health issue because oxygen is displaced by carbon dioxide molecule, resulting in oxygen level that reduces gradually regardless indoor or outdoor as taken from previous studies [25-28]. Therefore, adequate ventilation is important to ensure that the indoor CO_2 gas emitted by human activities is maintained at a diluted CO_2 level.

It is worth emphasising that the increased number of people appear in a classroom or laboratories with limited ventilation may increase the indoor carbon dioxide concentration because humans need a continuous respiration process by inhaling oxygen and exhaling CO_2 into the air to sustain the overall body functions and life. Indoor CO_2 concentration which exceeds 1,000 ppm will begin to cause sick building syndrome symptoms (SBSs). Furthermore, many studies have reported that humans who are exposed to CO_2 concentration of greater than 1,000 ppm or long periods may mildly or seriously affect their cognitive performance (including decision-making, speed of addition, problem resolution and creativity) based on different CO_2 concentration levels.

On top of that, CO_2 concentration of beyond 2,000 to 5,000 ppm may cause headaches, chest tightness, sleepiness, increase in heart rate. Cao *et al.,* [29] in a previous study showed that human cognitive performances were significantly impaired at 5,000 ppm of CO_2 concentration level.

Temperature and relative humidity are important factors to consider for improving indoor air quality at campus laboratories, workshop, offices or others indoor workspace. Temperature and relative humidity are correlated, and both can influence the indoor concentration level and distribution of air pollutants. On top of that temperature and humidity play a significant role in human comfort and health issue. The recommended indoor air temperature and relative humidity suggested by DOSH and ASHRAE [30] are indicated in Table 1.

Table 1
Recommended indoor environment air temperature and relative humidity

	Temperature	Relative Humidity	Reference
DOSH	23°C ~ 26°C	40% ~ 70%	DOSH [31]
ASHRAE	19.4°C ~ 27.7°C	30% ~ 60%	ASHRAE [30]

DOSH [31] recommended indoor air temperature and humidity to be in between 23°C — 26°C and 40 % — 70 % respectively, while ASHRAE recommended it to be within 19.4°C — 27.7°C and 30

% — 60 %, respectively. Temperature and relative humidity that has exceeded or is below the range could possibly affect human health. High temperature causes humans to breathe in difficulty, worsen respiratory conditions and have heat stress symptoms. Meanwhile, in low temperature increases risk of cardiovascular disease, lungs inflammation and worsen respiratory conditions. On the other hands, excess moisture in the air leads to heat stroke, fatigue and increases allergies infection. Low humidity levels lead to dry skin and eyes, throat and nose irritation.

1.3.2 Indoor environment air circulation

Indoor air quality also refers to the air quality of indoor environments, whereby it could influence the health and well-being of occupants. Maintaining good indoor air quality (IAQ) can be achieved through ventilation which can help to dilute indoor air pollutants, including carbon dioxide (CO_2), particulate matter (PM), VOC and other contaminants that are emitted from various building materials and human activities. Besides, indoor air ventilation may also contribute to control and influence indoor temperature and relative humidity.

An important aspect to consider is that the indoor air and outdoor air they are practically constantly exchanging through several of pathways (EPA United States Environment Protection Agency) such as infiltration, natural ventilation and mechanical ventilation. Appropriate ventilation system strategy implementation in a building is crucial because it determines a good and safe air circulation throughout the building to ensure that occupants are exposed to dilute or less polluted air. This is because people spend approximately 90% of their time within a building, whereby long-term exposure to high concentration pollutants in air may cause chronic or serious cardiovascular disease and asthma.

Infiltration, also known as the outdoor air, can flow into a building through gaps around the windows, doors, cracks in the walls, ceilings or via ventilation system leakages [32]. One significant impact to indoor air quality by infiltrating air will significantly degrade due to polluted air, especially particulate matter (PM) from outside entering the building if the outdoor air is contaminated with pollutants. Therefore, infiltration air that seeps through gaps contained in designed building is undesired. Another study from Fu *et al.,* [33] showed that indoor air purifier with high quality and efficiency multi-layer filters were required in order to improve and maintain the indoor air quality (IAQ) at healthy level caused by infiltration air.

Natural ventilation is somewhat alike with infiltration, but huge amount of air can enter buildings through opening windows, doors and vents. Natural ventilation occurs due to three natural factors which are temperature difference between indoor and outdoor, wind power around the buildings as well as the combination of both conditions to facilitate air circulation between outdoor and indoor air, Curd *et al.,* [34]. The main advantage of natural ventilation is that no power consumption and maintenance is needed as compared to mechanical ventilation system whereby all depend on the opening placement of supply and exhaust ventilation. However, natural ventilation is often relying on outdoor climate, slow or in-effectiveness of air movement that occurred during outdoor climate which have high temperature, humid and low winds speed. Previous study done, concluded that natural ventilation is an inappropriate solution to implement in buildings that are close to roadways because of the airborne pollutants' particles floating in air is high [35]. Mechanical ventilation system with added a fan to the indoor ventilation system is usually found in an air duct or directly in the walls, as well as air conditioning (HVAC) systems. The fans in the system will bring the outdoor air flow into indoor environments and exhaust indoor polluted air to ambient rather than relying on air flow via natural ventilation. Additionally, it should be mentioned that mechanical ventilation also has the ability to regulate indoor temperature and humidity in order to improved occupants' comfort

[36]. However, Rosli *et al.,* [37] implored that ventilation using air ducts mounted together can verily be susceptible to the detrimental of indoor air, where duct cleanliness correlates directly to the contamination of airborne indoors. Hence, it is imperative, to have a good maintenance such as regular cleaning of air ducts to prevent dust, debris residues and mold growth occurring in air ducts.

To summarise, natural ventilation and mechanical ventilation, using air ducts system is vital in order to improve healthy and safer indoor air quality. It shows that an indoor building with lesser air exchange rates will gradually resulting indoor air become sick this is because of the indoor air pollutants concentration levels such as carbon dioxide (CO_2,) particulate matter (PM), volatile organic compounds (VOCs), radon, and biological contaminants are not rapidly diluted and exhausted. On the other hand, higher air exchange rate may effectively improve indoor air quality however occupants or owners need to upgrade their ventilation system by installing or upgrading the HVAC systems or mechanical fans in air duct with filters. Consequently, energy consumption of the building will gradually increase.

1.3.3 Investigation of air quality in offices, classrooms, library and laboratories

Few past research had observed that the present mixture of liquid or solid particles which were categorised in PM_{10} (PM< 10 µg/m^3), and $PM_{2.5}$ (PM < 2.5 µg/m^3) in indoor environments, such as classrooms, laboratories, library and offices had surpassed the indoor air quality standards predefined by WHO. On the other hand, few research studies stated that carbon dioxide concentration levels in their investigated locations were maintained below DOSH standards while the CO_2 concentration exceeded 1000 ppm.

Further, taking from previous the studies concluded that increase in coarser, fine or ultrafine particles were highly related to various human physical activities that were conducted indoor [38-41]. Besides, indoor and outdoor air exchange rate is another factor which influence indoor air quality. In other word, high percentages of outdoor air particulates matter could have infiltrate indoor environment through opening or closing of doors and windows. Moreover, urban school in Qatar, campus office, library study room, and computer laboratories in Taiwan university obtained carbon dioxide results which pointed above 1000 ppm. Meanwhile, another investigation was done in laboratories, located in Terengganu University and another study done at IIT (ISM) Dhanbad university in India concluded that carbon dioxide concentration obtained was below ASHRAE standards of 1000 ppm. Both studies infer that human respiration and activities were the primary contributors in building up carbon dioxide at indoor environment. Taking from previous studies found other factors that influenced indoor carbon dioxide level which had insufficient air ventilation exchange rate between indoor and outdoor, as well as the size of the workplace whereby higher level of carbon dioxide gas was recorded when many people are carrying out activities in the same workplace and learning place [42,43]. Wijaya *et al.,* [44] in a previous study conducted a CFD (Computational Fluid Dynamics) simulation analysis to study air exchange rate in a classroom in order to improve air flow. Based on the air flow analysis carried out on the ventilation layout configurations, it was concluded that a selected type of ventilation configuration can be optimised to improve a better air exchange rate.

2. Methodology

This investigation project was conducted at the materials and automation laboratory (M&A Lab), and engineering workshop in University of Wollongong Malaysia. The material and automation laboratory consisted of four air-conditioning systems, mechanical ventilation systems, doors and windows. The laboratory was equipped with many fabrication machines, including CNC lathe machine, CNC milling machine, pyrolysis heating equipment, granulator machine, laser cutting machine, sieve machine, oven, and drilling machine. The engineering workshop consisted of mechanical ventilation systems, roller shutter gate, exit doors and windows. It was also equipped with many fabrication machines, tools and stocks including lathe machine, milling machine, drilling machine, and bandsaw machine.

Figure 2 shows the overall prototype model system. Three distinguished sensors were used to measure the air quality and data were fed onto the Raspberry PI controller. This controller was selected due to its compact size and versatility, which was suitable to be implemented in the monitoring system. The Raspberry PI controller had with a microSD card pre-loaded with Linux operating system. The sensors communicate with the controller system by using NodeMCU ESP32 as a device-to-device wireless communication via a cloud server. Such connectivity will allow sensors to feed the data wirelessly to the controller in real-time. The controller outputs the data to the computer monitoring which have an Influx DB database installed and Note-Red program written for interfacing with GUI (Graphic User Interface) Grafana Dashboard software dashboard for data visualisation.

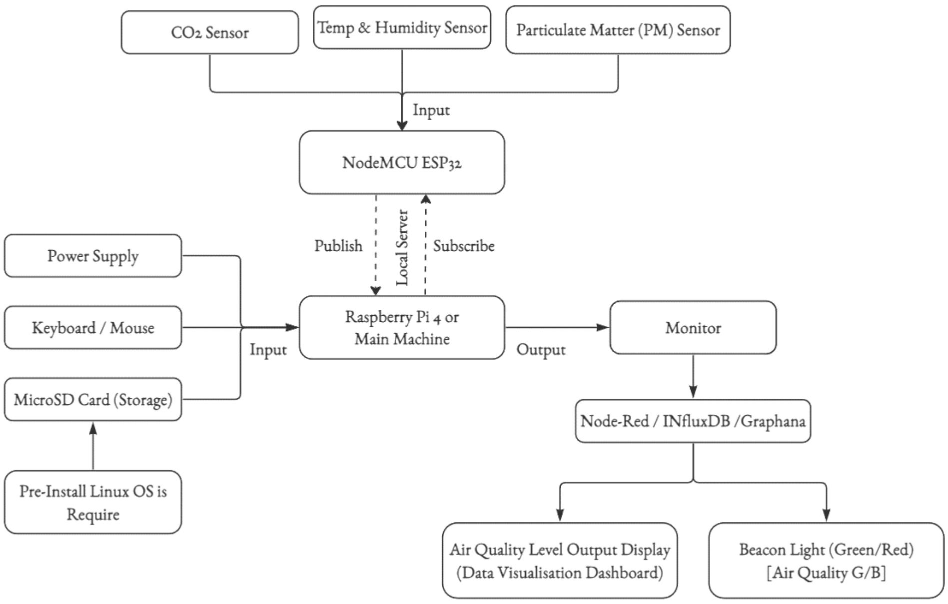

Fig. 2. System development block diagram which consists of controller, sensors, and dashboards

Figure 3 shows the designed, developed and implemented indoor air quality meter which consisted of SHT30-D temperature and relative humidity sensor, MH-Z14A carbon dioxide sensor, SDS011 Nova Particulate Matter Sensor, and ESP32 modules, which were mounted on a 3D-printed standoff stud, respectively. Each standoff stud was pre-set with a specific size of threaded brass insert. Therefore, sensors and modules were fixed by a machine screw with a custom-made bush to ensure it remain stable and secured within the housing. The complete measurement module unit was placed in the middle area, adjacent to the workbench where students worked.

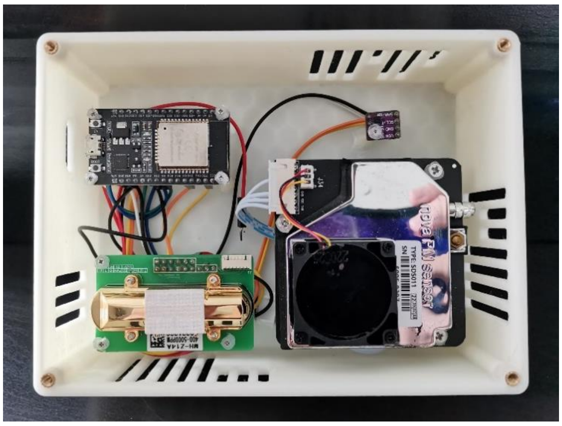

Fig. 3. Complete Sensor Measurement and Communication Module

Figure 4 shows assembled warning tower light display unit, whereby an industrial RYG tower light was mounted on pre-drilled 5.0 mm holes at the top casing of the enclosure box by using 5.0 mm diameter bolts and nuts. RYG and ground wires were passed through the drilled hole created in the centre of the 4 bolt holes which were used to fix the RYG tower light. AC/DC converter and 3- channel relays were positioned and fixed inside the enclosure box. The power supply cable and trigger wires were connected to the 3-channel relay and were passed through a pre-drilled hole located on the side of enclosure box. This was done so that the wiring connection for the warning light display unit was all organised in a box for easy management.

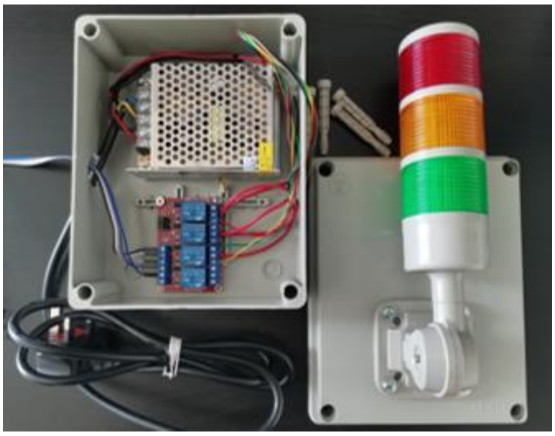

Fig. 4. Beacon Light Indicator for alert system

Figure 5 shows the developed Grafana dashboard for monitoring real-time parameters. This IAQ dashboard was designed and developed by using Grafana data visualisations platform which was integrated with Influx DB, Node-Red server, and sensor measurement. This dashboard provided gauge and time series graph visualisations in two separate sections. First section showed 5 different indoor air quality concentration level in gauges visualisations, each parameter gauge was configured with specific thresholds limit based on WHO air quality standard, which means that the gauge colour will turn to a warning colour when the real-time IAQ concentration exceed set threshold. The second section provides current and historical air quality data of the day in time series graph visualisations, which broken to five IAQ parameters, including temperature, relative humidity, carbon dioxide, particulate matter 2.5, and particulate matter 10. The time ranges and refresh rate features on the dashboard were set based on various specific needs.

Fig. 5. IAQ Remote Monitoring Dashboard displaying Real-Time Data by using Grafana software

Real-time accessibility enabled the office staff to monitor the air quality of UOWM laboratories and give warning to laboratory users. All data collected will be benchmarked against WHO IAQ guidelines on carbon dioxide and particulate matter and DOSH IAQ guidelines for temperature and relative humidity.

The complete system measurement is in Figure 6. The indoor air quality dashboard displayed in a monitor A represented the monitor display unit in the laboratory staff office to remotely monitor laboratory air quality. The indoor air quality meter, warning light display unit and Monitor B was positioned in the laboratory. To be specific, the indoor air quality meter was positioned at the central location of the laboratory, whereby Monitor B and warning light display unit were positioned on the wall right beside the door. This approach ensured that the meter measured the average indoor air pollutant concentration more accurately as indoor air flow or circulation motions of a room can vary. It was recommended to position an indoor air quality meter at the center area in the laboratories to avoid air disturbance from outdoor air.

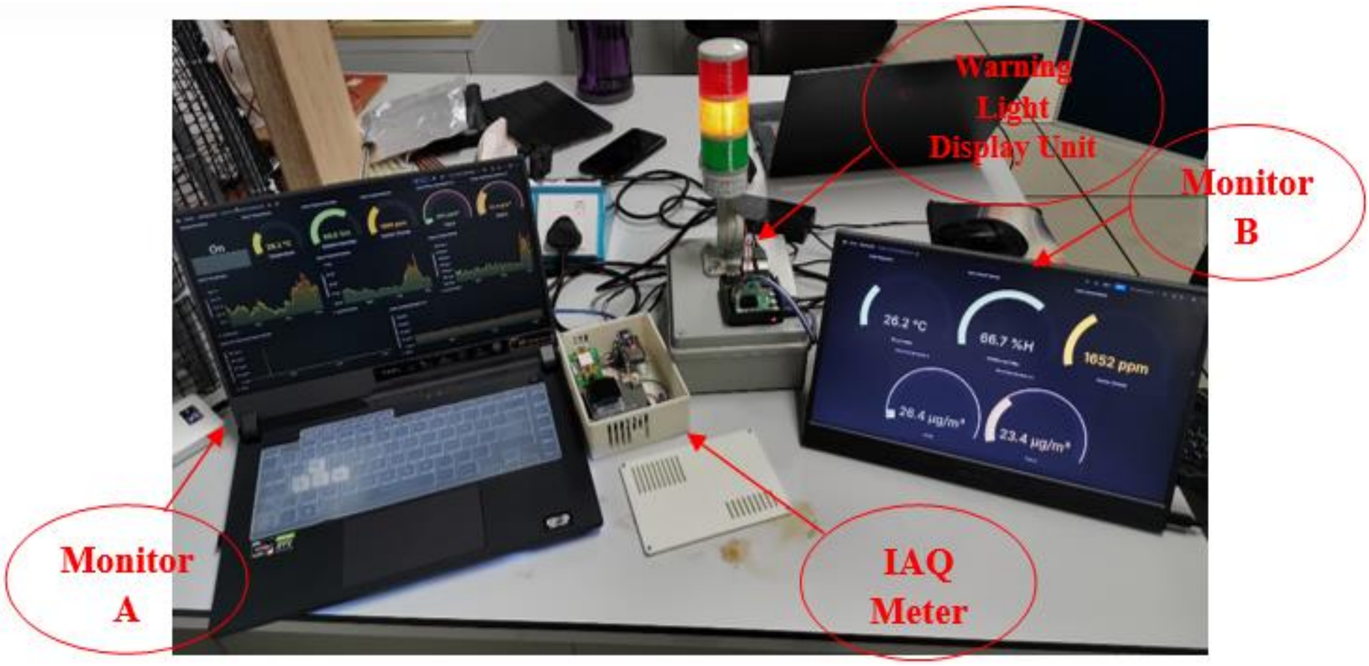

Fig. 6. Complete IAQ alert system displaying Real-Time data by using dual monitors

The beacon light turns green when the air pollutants are within air quality guidelines set limits. It turns to yellow light when one or two air pollutants exceed the air quality guidelines set limits while it turns to red light when three of the air pollutants exceeded the set limits. This method allows the students or staff working in the laboratory to respond rapidly to take immediate action to neutralise indoor air by opening windows, doors or ventilation systems. The indoor air quality meter and datalogging device developed were positioned at the center area of the laboratory and workshop to collect indoor air parameters level and air pollutants concentration for 8 hour (with an interval of 1 hour) for three days. Data were logged in CSV format by using Influx DB database and further integration with Grafana Dashboard.

3. Results

3.1 Temperature and Relative Humidity

Table 2 shows data tabulation for temperature and relative humidity for the material and automation laboratory and workshop. Data were collected continuously 8 h for three days; hence, only the minimum and maximum values were tabulated, while the mean data was calculated at every 1 h interval up to 8 h maximum of measurement.

Table 2
Temperature and Relative Humidity data collected

Materials and Automation Laboratory						
Parameters	Temperature, °C		Mean (SD)	Relative Humidity, %		Mean
Day 1	24.6	27.8	25.9±0.96	67.2	79.8	73.9±3.98
Day 2	26.2	26.7	26.4±0.15	63.3	72.2	69.3±3.62
Day 3	25.7	27.2	26.6±0.54	62.5	71.1	65.5±3.171
Engineering Workshop						
Parameters	Temperature, °C		Mean (SD)	Relative Humidity, %		Mean
Day 1	28.3	29.1	28.7±0.2892	63.7	74.4	67.4±3.86
Day 2	28.5	29.1	28.8±0.2048	63.4	74.2	68.1±4.23
Day 3	29.4	31.4	30.3±0.6051	60.8	63.4	61.7±0.74

In the Materials and Automation laboratory, the mean temperature for day 1, day 2 and day 3 were 25.9±0.9631 °C, 26.4±0.15 °C and 26.6±0.54 °C, respectively, and it can be concluded that the laboratory temperature was acceptable according to air quality standards range of 23 °C - 27.7°C. (DOSH). It was also noted that the maximum temperature for the past three days exceeds the maximum limit by approximately 1 °C.

The mean relative humidity values were 73.9±3.99 %, 69.3±3.62 %, and 65.5±3.17 % for Day 1, Day 2, and Day 3, respectively. It was observed that for Day 1, the mean relative humidity exceeded the upper limit threshold. For Day 2 and Day 3, the mean relative humidity showed readings that almost exceeded the maximum limit threshold, referring to the DOSH standard. Despite the mean values of the relative humidity were acceptable, it was noted that for Day 1, the maximum value reached at 79. 8 %, and thus exceeded the limits of 70 % (DOSH). It was noted that, the lower temperature gave rise to higher humidity level. Therefore, in such case of exceeded humidity level, the Beacon light indicated a red alert, suggesting that prompt action was needed to be taken by laboratory staffs.

In the engineering workshop, mean temperature for Day 1, Day 2 and Day 3 were 28.7±0.29 °C, 28.8±0.20 °C and 30.3±0.60 °C, respectively. It could be observed that the minimum and maximum recorded temperatures for Day 1, Day 2 and Day 3 had exceeded the recommended DOSH limit range between 23°C and 27.7°C. Therefore, the exceeded temperature value, might turn on the Beacon light alert. For the relative humidity, mean data analysed for Day 1 are 67.4±3.86 %, for day 2 is 68.1±4.2 %. For day 2, the mean value is at 61.7±0.74 %. The minimum and maximum RH values were within the acceptable range of DOSH limit. The higher temperature reading caused the humidity level to be lower.

Data from both laboratory and workshop concluded that the temperature corelated with humidity level, whereby temperature was inversely proportional to humidity. However, a balance between these two parameter values must be in conformity with the required guidelines. A rising temperature might not be conducive for students to work in these locations. Should the temperature rise, the air capacity is able to accommodate more moisture, resulting in students to have discomfort, sweaty feelings and lose their focus on the activities.

Suppose the temperature keeps rising, assuming the moisture contents in air remains constant, this would lead to lowering of relative humidity. Generally, such locations may have the air conditioning operating to reduce temperature, this apparently would cause higher relative humidity. Such condition may lead to condensation on machines or other related operating electrical appliances.

3.2 Carbon Dioxide Concentration

Table 3 shows the 8 h of data collected for carbon dioxide concentration and mean value of average concentration calculated for Day 1, Day 2 and Day 3 on material and automation laboratory and engineering workshop. Materials and automation laboratory CO_2 concentration mean ppm value was at 367ppm for Day 1, 426 ppm for Day 2 and 482 ppm for Day 3. As compared to the workshop, there was a significantly higher mean value of CO_2 analysed, whereby the mean ppm value was at 417 ppm for Day 1, 405 ppm for Day 2 and 489 ppm for Day 3. However, the concentration of CO_2 level was concluded to be within the limits based on the air quality guidelines by the World Health Organization (WHO) that sets the limit of CO_2 concentration to be less than 1000 ppm.

Table 3
Carbon Dioxide (CO_2) concentrations collected

CO_2 (ppm)	M&A Lab			Workshop		
Days	Min	Max	Mean ± (SD)	Min	Max	Mean ± (SD)
Day 1	287.2	543.3	367.7±78.1	345.1	485.4	417.4±67.4
Day 2	341.2	517.5	426.6±57.9	375.7	435.8	405.6±18.1
Day 3	378.7	566.6	482.7±66.7	378.2	645.9	489.4±81.4

Although the fact concluded that the CO_2 levels under the WHO standards were comforting, there was reason for concern since the maximum values were 566 ppm and 645 ppm for both areas. Both laboratory and workshop had an existing window panels and ceiling mounted exhaust system; however, during the time of sampling measurement was done, the windows were closed, and exhaust system was not working up to its full efficiency. In such conditions, there was a possibility that air circulation in both spaces (laboratory and workshop) remained insufficient to neutralise carbon dioxide gas. The values measured were still rather high, even if they were well below the 1000 ppm criterion. There could be a symptom of inadequate ventilation or other problems that possibly have an impact on students' comfort and quality of indoor air. Continuous monitoring and improvement of air quality is necessary and addressing the CO_2 sources in order to maintain more lower levels should improve indoor environmental quality and students' health.

3.3 Particulate Matter Concentration

Table 4 shows the particular matter 2.5 μg/m^3 and 10 μg/m^3 ($PM_{2.5}$ and PM_{10}) measured and tabulated along with the mean standard deviation. In the Materials and Automation laboratory particulate matter, PM_{10}, its average dispersion from mean were 16.1±3.43 μg/m^3, 70.1±60.41 μg/m^3, and 76.2±23.97 μg/m^3 for three separate sampling days. The recommended limit set by WHO, whereby PM_{10} limits should be less than 45 μg/m^3 and $PM_{2.5}$, was to be less than 15 μg/m^3. Benchmarking with these guidelines observed that the PM 10 concentration exceeded the limit for day 2 and day 3, with the highest concentration recorded at 197 μg/m^3 on day 2.

Table 4
Particulate Matter data recorded and analyzed

Materials and Automation Laboratory						
Parameters	PM_{10}, μg/m^3			$PM_{2.5}$, μg/m^3		
Days	Min	Max	Mean ± (SD)	Min	Max	Mean ± (SD)
D1	9.89	19.7	16.1±3.4295	8.9	15.5	12.7±2.0366
D2	30.1	197.7	70.1±60.41	26.9	69.6	38.1±15.4412
D3	49.0	122.0	76.2±23.9606	31.7	86.6	57.5±19.3349
Engineering Workshop						
Parameters	PM_{10}, μg/m^3			$PM_{2.5}$, μg/m^3		
Days	Min	Max	Mean ± (SD)	Min	Max	Mean ± (SD)
D1	32.6	51.5	40.2±5.6458	26	39.6	31.5±4.2213
D2	31.7	40.3	35.8±2.9232	25.8	30.9	28.0±1.6294
D3	35.9	120.6	63.4±38.9609	27.8	60.2	40.6±11.3259

Data tabulated for $PM_{2.5}$ on day 1, day 2 and day 3 were 12.7±2.04 μg/m^3, 38.1±15.44 μg/m^3, and 57.5±19.33 μg/m^3 respectively. Based on the WHO guidelines, $PM_{2.5}$ concentrations in this laboratory also exceeded the limits. The maximum value recorded was on day 3 at 86.6 μg/m^3. Based on these data, it was concluded that both PM_{10} and $PM_{2.5}$ exceeded the safety threshold recommended by WHO. It was observed that during day 2 and day 3, there were plenty of student activities conducted in these areas. The experiments that were conducted over the 2 days were pyrolysis treatment, operations of CNC machines, milling machines running, materials placed on open storage was exposed to air, heating of materials and many more activities relating to material experiments. It was to be noted that the mentioned activities were of daily use of the laboratory.

Engineering workshop PM_{10} concentrations for day 1, day 2, and day 3 were 40.2±5.6458 μg/m^3, 35.8±2.9232 μg/m^3, and 63.4±38.9609 μg/m^3, respectively. Fine particle $PM_{2.5}$ concentration mean and standard deviation for day 1, day 2, and day 3 were 31.5±4.2213 μg/m^3, 28.0±1.6294 μg/m^3, 40.6±11.3259 μg/m^3, respectively. For PM_{10}, it could be considered that the measurement was at the borderline of the limit threshold; however, for $PM_{2.5}$, it exceeded the limit with the highest deviation at 25 μg/m^3. It was well noted that many fabrication processes, welding process, cutting and grinding of metals as well as collection of metal waste exposed, potentially produced more of $PM_{2.5}$ suspended in air. Similarly, rising temperatures with lower humidity could affect particulate matter concentrations for both PM_{10} and $PM_{2.5}$. These particles could either enlarge or shrink depending on the humidity level.

It is crucial to take immediate action to stabilize air quality by optimizing the current exhaust and ventilation system. The workshop was fitted with the exhaust duct however, its location mounted in the workshop may not be feasible enough to operate in mitigating $PM_{2.5}$ and PM_{10}.

On another note, during the experiment, the Beacon light operated based on the high reading that was exceeded. However, the alert system was not applied for the carbon dioxide reading. Therefore, the dashboard reading was crucial enough to display various readings and it was imperative for personnel in charge to mitigate such problems in air quality.

4. Conclusions

The indoor air quality remote monitoring system, indoor air quality meter device with data logging system and indoor alert system were designed and developed through integration with multiple applications including the Internet of Things (IoT) MQTT messaging protocol, Node-Red, Influx DB and Grafana. The whole system was implemented and tested at the selected laboratories and two different monitor devices were able to display real-time air parameters by using the Grafana Dashboard. In order to present it as an alert system, a Beacon light was integrated with the controller. The Beacon light which consisted of red, green, and amber, gave a visual indicator on air quality inside the laboratory and workshop, monitoring the safety threshold parameters of temperature, humidity, carbon dioxide and Particulate Matter.

These air quality components were measured and displayed in real-time and were being investigated. It was found that both Material and Automation laboratory and the engineering workshop were experiencing air quality issues that could be detrimental to the comfort and chronic health of students and staff. Additionally, the engineering workshop was noted to be warmer than the Material and Automation Lab. A visual inspection done at this workshop observed that there was no air conditioning system installed to control the air temperature and relative humidity. Nevertheless, having an installed fan blower may not be able to reduce the rising temperature. Similarly, the Material and Automation laboratory had inadequate ventilation and an exhaust system installed may not be able to reduce the temperature to a comfortable level. Observing the physical conditions of the laboratory and workshop, it provided a definite conclusion on the reasons for the high concentration of particulate matter being recorded. Moreover, the indoor air quality assessment done for both locations, benchmarking with WHO and DOSH IAQ guidelines, justified the student survey data depicted in Figure 1 on experiencing dusty smells and strong odour emanating from surrounding activities.

Nevertheless, the data collected was for 3 days, and thus this project could be further extended to longer periods in collecting data. Besides, further investigations required on the volatile organic compound (VOC) measurements. Future works undertaken is to have a CFD (Computational Fluids Dynamics) to analyse the air flow for new laboratories and gauge the suitableness or worthiness in implementations of exhaust system, ventilation viaducts and other retrofitting works.

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