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Analysis of Indoor Air QualityBased on Low-Cost Sensors

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***Abstract*— According to WHO, indoor and/or outdoor air pollution is one of the main contributors to over two million premature deaths each year. As most of the human's life is spent indoor, Indoor Air Quality (IAQ) – an air quality inside of a building represented by pollutant concentration and thermal condition – is one factor that needs to be concerned to sustain healthy living. In this research, we developed an Internet of Things (IoT)-based IAQ monitoring device using low-cost sensors that measure the concentrations of Carbon Dioxide (CO_2), Oxygen (O_2), and Particulate Matter ($PM_{2.5}$). This device connects to an Android application to further observe these parameters inside two practicum laboratories in Telkom University, Bandung, for a total duration of six weeks. The location is surrounded by urban air pollution, particularly industrial activities, and residential waste burning. We also have sites of outdoor air quality monitoring system for simultaneous measurement. The environmental conditions were observed under no human activities, human intervention, and indoor plants' influence (i.e., Dieffenbachia sp.). Results show that pollutant concentrations are considerably influenced by outdoor conditions, occupancy level, and ventilation rate. Indoor plants can reduce CO_2 concentrations inside the room (21-47%). On the other hand, there is no clear evidence that $PM_{2.5}$ mass concentrations were affected by human activities. The bigger particles (PM >2.5 microns) probably were the ones induced by occupants during practicum. Therefore, using low-cost sensors is trustworthy to monitor IAQ for a better quality of life.**

***Keywords*— CO_2; internet of things; indoor air quality; low-cost sensors; $PM_{2.5}$.**

I. INTRODUCTION

Lately, urban air pollution has been a worrying problem for humans. We have been somewhat reluctant to come from unintended air-polluting activities or went as a well-known by-product from other actions. Urban air pollution should be a significant concern for this new decade that we are entering. It has been proven for us visually as there was a lot of smog phenomenon reported in recent years in large urban areas around the world, such as in Beijing (2019), Jakarta (2019), Southern Europe (2020), and others. Despite all the effort, in Europe alone, EEA reported that in 2016, an estimate of 412,000 premature deaths occurred can be attributed to air pollution exposure of $PM_{2.5}$. In addition to that, NO_2 and O_3 exposure added around 86,100 to an already massive number of premature deaths [1].

The recent air quality guideline by WHO has stated that two million premature death globally each year is attributed to urban outdoor and indoor air pollution [2]. Adding a statement that indoor air pollutants can be 2-4 times higher than its outdoor counterpart [3], the indoor environment inside urban cities is even more worrying about its magnitude of the effect, as humans spend 93% of their life indoor [4]. Thus, it has made indoor air quality (IAQ) – a quality factor affected by indoor air pollutants – as a considerable factor affecting our health and well-being.

The definition of IAQ is still in its "elusive" state [5]. I-BEAM (IAQ-Building Education and Assessment Model), an assessment and standardization in building modeling done by Environmental Protection Agency (EPA), refers to IAQ as an air quality inside a building that is represented by pollutant concentrations and thermal condition (relative humidity and temperature) [6]. So far, there is no quantitative way to define how poor or good IAQ inside indoor living space is. However, referring to standards of maximum or minimum exposure of pollutant concentrations and thermal conditions have been approached to illustrate IAQ. Meaning, good IAQ for an indoor living space will have pollutant concentrations and thermal condition range within the ratings and bad IAQ exceeding or at the rating range.

Meanwhile, from a health perspective, poor IAQ (or high concentration of Indoor Air Pollutant (IAP)) can lead to discomfort, decreased productivity, and very dangerous for the elderly, children, and people with respiratory illnesses [7]. IAP, such as $PM_{2.5}$ and CO_2 in the indoors, can lead to some health conditions. Excessive $PM_{2.5}$ exposure can lead to respiratory illness, cardiovascular illness, diabetes mellitus, congenital disabilities, etc. [8]. Also, excessive CO_2

exposure can lead to arrhythmia, convulsions, unwanted anesthesia, and others [9]. Meanwhile, not belonging to a pollution group, insufficient exposure to O_2 can lead to unconsciousness, hypoxia, and others. By this statement, IAQ monitoring is needed further to assess the air quality situations in indoor living spaces.

A study conducted in 2017 of IAQ measurement in several households in Macedonia using the industrial instrument (measuring TVOC and PM), [10], was deemed to be quite expensive and complicated for a novice researcher or even as household tools. With all analyzer (sensor) combined costing more than 5000 USD and came as a separate system, it is considered costly and not easy-to-use for continuous monitoring of IAQ. Another study conducted in 2016 of IAQ measurement in North Taiwan’s Metro System [11], with even more IAQ parameters, also faces even more significant complications and cost.

Recently, the emerging lines of low-cost sensors in the market have been intriguing to many researchers. Although there is no agreed definition to which sensor is a low-cost sensor, in this research, any sensors costing less than the main measuring instruments but still integrating them in their development is considered a low-cost sensor. As low costing as these sensors get, they must achieve a reliable measurement to be massive and feasible for commercial or even study applications. The low-energy and high-integration properties of these sensors had led the writer to take advantage of this new technology. In a study conducted in Brazil, researchers combine several low-cost sensors into an embedded system that have been proven to be effective in mapping IAQ inside a building [12].

In this study, we integrated a device using these low-cost sensors to measure some indoor air quality parameters: concentration of CO_2 and O_2 gas, concentrations of $PM_{2.5}$, and condition of Relative Humidity (RH) and Temperature (T). Before the measurement is conducted, we also validated and calibrated these low-cost sensors. These parameters are measured in two laboratories located in the School of Electrical Engineering, Telkom University – an urban area located in Bandung districts. Three different phases/conditions were conditioned for this measurement: without human intervention, around human intervention, and controlled plant placement inside the indoor living spaces. We also have outdoor air quality monitoring sites that measure simultaneously with the indoor measurement for further observation. Overall, this research aims to thoroughly analyze the IAQ of indoor living space in the urban area through the three parameters, observe the influence of occupancy rate to IAQ, observe the influence of indoor plants on IAQ, and the end raise the awareness of IAQ importance.

II. MATERIALS AND METHOD

A. Low-Cost Sensors

In this research, we use three low-cost sensors to create an air quality monitoring device. These sensors are selected because of their detection range that is suitable for indoor measurement. Before the research measurement is conducted, these sensors were tested to assure further the measurement that they will be taking.

The CO_2 sensor (Sensirion SCD30) that we use detects the concentration of CO_2 (in ppm) using the NDIR (Non-Dispersive Infra-Red) method. The CO_2 sensor is tested by calibrating it. The calibration is done by comparing one sensor's readings with another that measures the same parameter and uses the NDIR principle (DFRobot SEN:0219) inside a measuring chamber. The DFRobot SEN:0219 was calibrated in previous research by comparing it with Lutron GCH-2018 with a result of $R^2=0.5$.

Using the CO_2 gas source, we simulate that the sensors' measurement will be at the maximum level of its measurement range. After the measurement reaches the maximum level, all air inside the chamber will be pumped out slowly. The sensors have time to read through their ranges in some degree of the interval until the sensors read the minimum level of its measurement range.

After all the sensor readings during calibration are gathered, we plot this data to a graph (See Fig. 1) and observe quite a linear line. From this graph, we analyzed these data using linear regression and manipulated it to fit the ideal line (reference line) roughly. We have done this by inverting the linear regression equation and subtracting it with its standard error deviation—the results in a correction factor that will further be used to adjust the measured data.

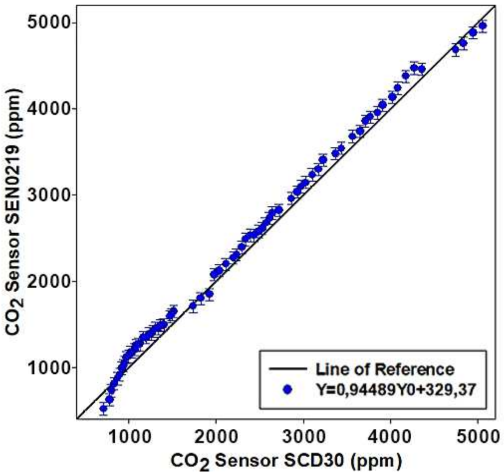

Fig. 1 Calibration result for the CO_2 sensor

The O_2 sensor (Winsen ME2-O2) that we use is an electrochemical sensor that detects the concentration of O_2 (in % [Vol/Vol]) through the reaction of electrolyte in it. The O_2 sensor, in this research, is tested by seeing the sensor fluctuates when given in different conditions of the O_2 level. Since the sensor measures in volume/volume (%) unit, we should see the lower reading of the O2 level when the sensor is exposed to a high concentration of other gas.

In this validation, Firstly, we measure a background O_2 level inside a measuring chamber. We could see a background reading of the O_2 level around 21%. After that, we slowly introduce some amount of highly concentrated CO_2 gas inside the chamber by pumping it in. With this validation technique, we see that the reading of the O_2 sensor goes down when the CO_2 gas is introduced (see Fig. 2). It means that the sensor can detect the fluctuation of the oxygen level that happens. Since the sensor manufacturer stated in the datasheet of the sensor that the sensor should not be exposed to the condition of high concentration gas, the sensor that measured the data presented in section 3 is a brand-new sensor of the same product.

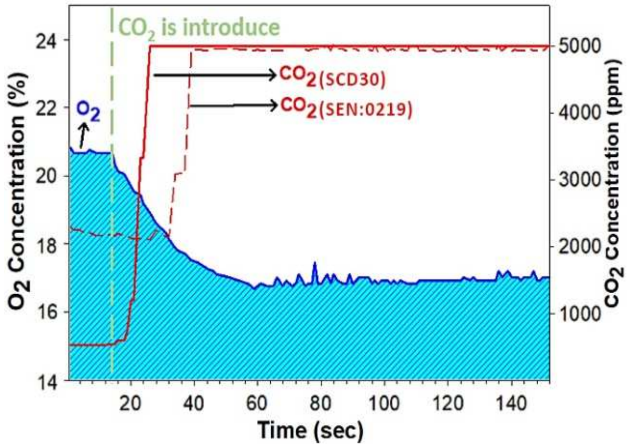

Fig. 2 Test result for the O_2 sensor

The $PM_{2.5}$ sensor (DFRobot SEN:0177) that we use detects the mass concentration $PM_{2.5}$ (in μgm^{-3}) by using a light scattering principle. The testing of this sensor is done by calibration conducted in previous research. The calibration is done by comparing the sensor reading with a primary instrument to compare the readings' differences. After comparing it, we conclude a correction factor to be applied to the measured data [13].

B. *Indoor Air Quality Monitoring Device Based on Low-Cost Sensors*

Utilizing the three low-cost sensors together, we make an Indoor Air Quality monitoring device. Using DC adaptor as a power supply for the device, we utilized a microcontroller board that connects to the sensor's proprietary pins (via circuit board) to obtain sensor readings (See Fig. 3). This microcontroller board also acts as a client and will send all the gathered data to the server. The data can then be retrieved via an Android application for intensive monitoring (See Fig. 4) or downloaded for further analysis. Some features for this application is a continuous reading of the parameters in the graph/numbers, and take/save pictures of the current place that are being measured. In further utilization of this device, this application can be shared widely for even greater use.

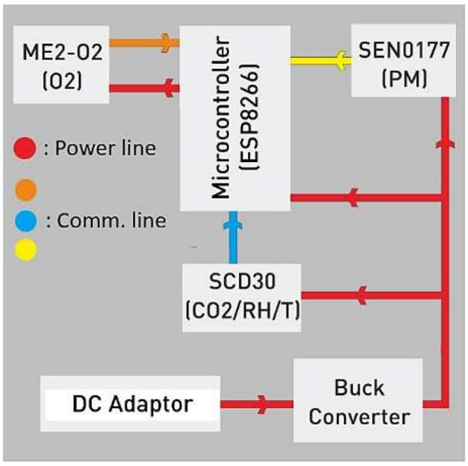

Fig. 3 Indoor air-quality monitoring system diagram

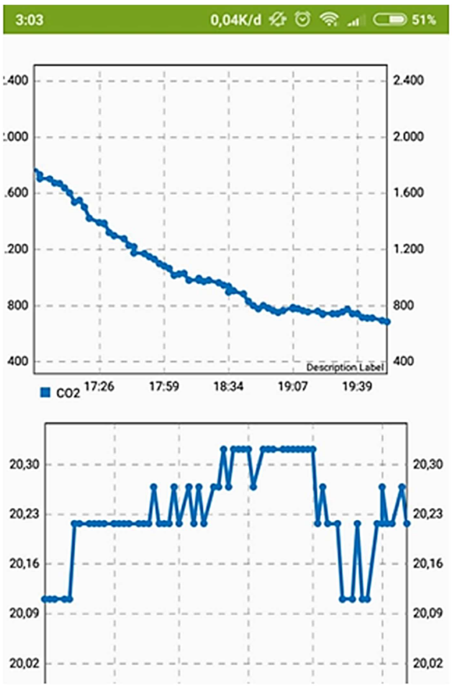

Fig. 4 Snapshot of the Android application for monitoring

C. *Sampling Sites and Sampling Method*

All the data given in this research are measured inside two indoor living spaces located at the School of Electrical Engineering, Telkom University, Bandung districts, an urban area surrounded by industries and about 2 km away from the border Bandung city. Both indoor living spaces are a practicum laboratory facility, namely Lab I and Lab II. The Lab I, which is a Basic Physics Laboratory, is located on the third floor of four stories building (namely Deli Building) with a room dimension of 11 x 7 x 2.5 m^3 and occupant of around 45 people when practicum is ongoing. Meanwhile, Lab II, a Computer Laboratory, is located on the first floor of three stories building (Namely N Building) with a room dimension of 15 x 10 x 2.5 m^3 and occupant of around 50 people when practicum is ongoing.

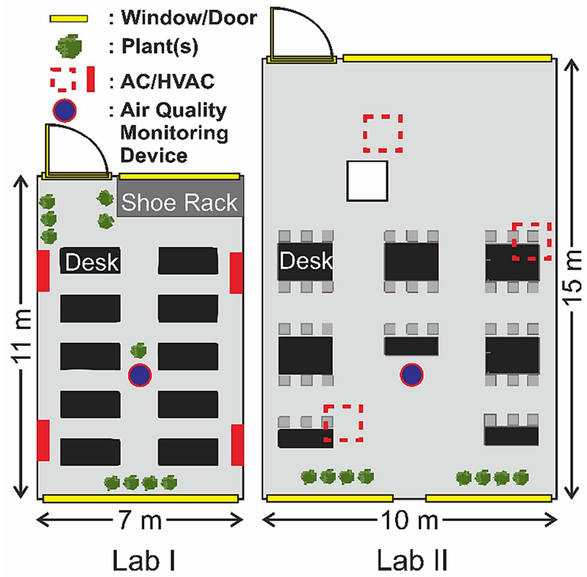

Fig. 5 Sampling sites layout

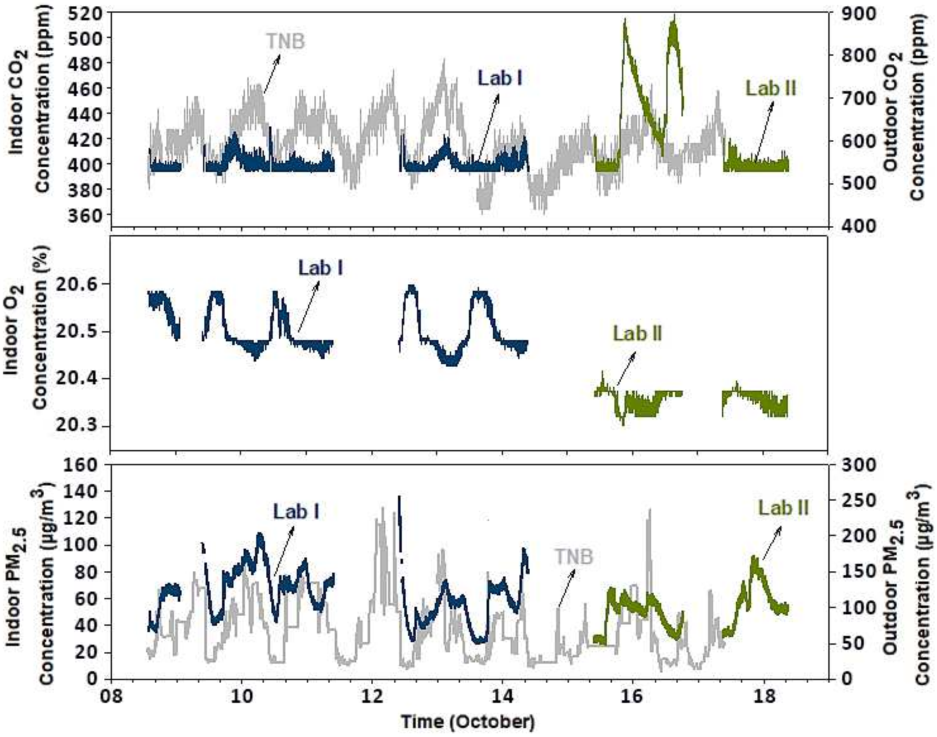

Fig. 6 Atmospheric concentration of CO_2, O_2, and $PM_{2.5}$ in Lab I and II

Both laboratories have air conditioning, furniture, and practicum tools installed. Fig. 5 is shown to understand the layout of each laboratory better. Aside from these two labs, two outdoor air quality stations simultaneously measured CO_2 and $PM_{2.5}$ on the nearby outdoor facility's roof, i.e. Tokong Nanas Building (TNB) and Deli building. TNB has located ~309 m and ~406 m away from Lab I and Lab II, respectively. However, due to equipment malfunctions, data from the Deli building station (closest to the two labs) were not included in this research.

Air quality data gathering in Lab I and II is conducted in three different phases. The first phase being a measurement when there are no human interventions involved and is aimed to see the overall atmospheric condition of the two labs. The second phase being the measurement around the human intervention. It means that the measurement is conducted when the occupants are doing their day-to-day activities, which are weekly based practicum. The last phase is the second phase's measurement condition with the control of indoor plants inside these indoor living spaces. This measurement aims to see the influence of plants on IAQ. Each phase is completed in a week for each indoor living space in a weekly continuous measurement. Thus, all the measurement is completed in six weeks. Alongside all these three phases, the air quality station on TNB is continuously measuring.

III. RESULTS AND DISCUSSION

A. *Atmospheric Pollutant Condition*

Atmospheric pollutant conditions where there is no human intervention involved in the first measured and tested in the Lab I and Lab II, also simultaneously in TNB. From Fig. 6, we can see that indoor and outdoor CO_2 and $PM_{2.5}$ concentrations have a similar trend of fluctuation, although a little shifted. Note that the primary source of these parameters was when there was no human activity inside, which came from the outdoor air. Although these labs are in the closed condition (meaning closed windows and doors), outdoor air can still enter through the windows and doors gaps and other gaps available for the air to enter. Meanwhile, shifting trends in the graph between indoor and outdoor measurements could be due to the distance of TNB from the labs. The previous study that conducted a measurement of CO_2 and $PM_{2.5}$ on the roof of TNB and Deli building (the building where Lab I is situated) simultaneously proved that there was a delay time of measurement between the two sites measured due to wind conditions [13].

The 8-hours average of CO_2 concentrations for Lab I and Lab II are 421 ppm and 402 ppm. These concentrations are still below the standard quality of maximum CO_2 concentration stated in Health Ministry of Indonesia Law No 1007/MENKES/ PER/V/2011, which is 1000 ppm per-8-hours per person.

Meanwhile, the average of O_2 concentrations for Lab I and Lab II are 20.4% and 20.5%. These concentrations are still above the lower limit of O_2 standard quality concentration released by OSHA, which is 19.5% [14].

Unlike CO_2 and O_2 concentrations, the 24-hours average of $PM_{2.5}$ concentrations for Lab I and Lab II are 51 μgm^{-3} and 52 μgm^{-3}. These concentrations exceeded the standard quality of maximum $PM_{2.5}$ concentration stated in the Health Ministry of Indonesia Law No 1007/MENKES/PER/V/2011, which is 35 μgm^{-3} per-24-hours per person.

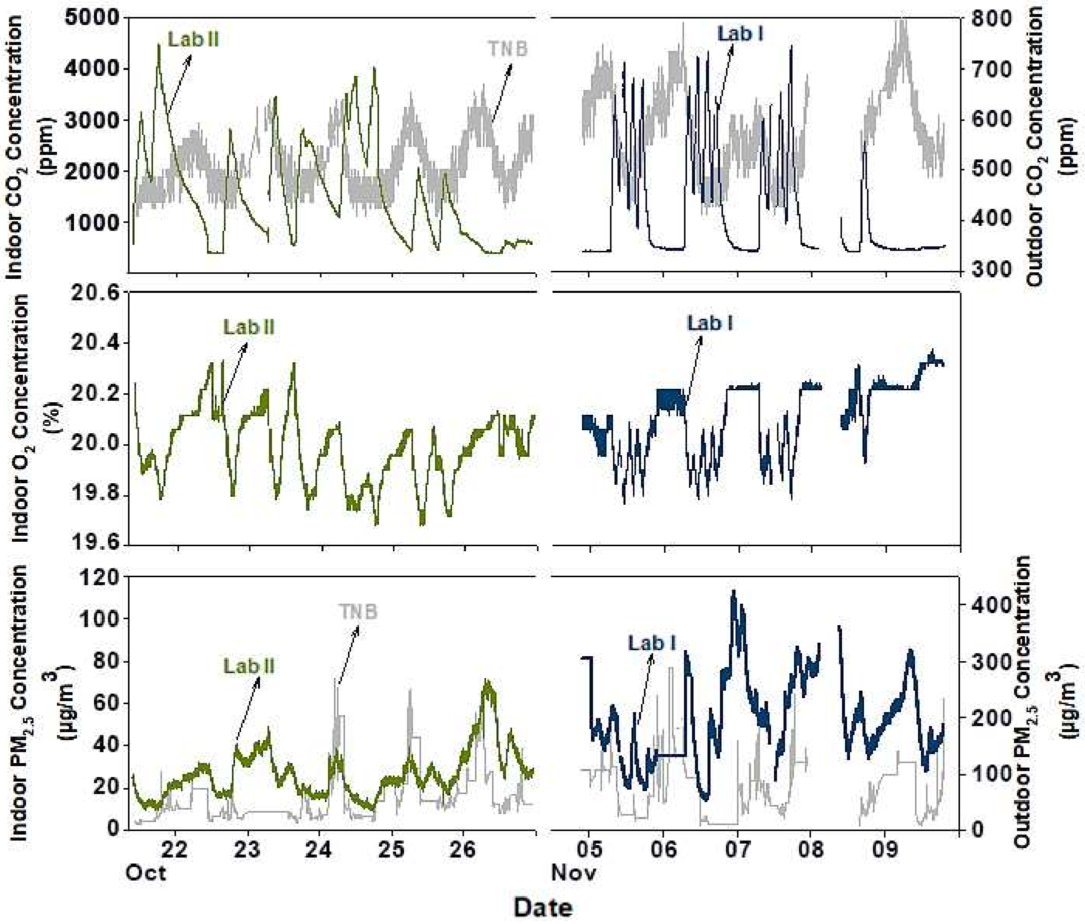

Fig. 7 Concentrations of CO_2, O_2, and $PM_{2.5}$ in Lab I and II with human intervention involved

B. *IAQ Around Human Intervention*

The results of CO_2 and O_2 concentrations in Lab I and Lab II when there are human activities (practicum) show significant changes in CO_2 and O_2 concentrations. As seen in Fig. 7, when there is a practicum activity, the CO_2 concentration has increased significantly while the O_2 concentration has decreased. CO_2 concentration when there is no practicum in Lab I and Lab II is in the range of 393-518 ppm and 391-430 ppm, whereas when there is practicum activity, the concentration of CO_2 in Lab I and II rises to reach 4501 ppm and 4449 ppm. The increase in CO_2 concentrations in Lab I and Lab II when there was human activity reached 6.6 and 6.4 times compared to the CO_2 concentration in Lab I and Lab II when there was no activity. A decrease in O_2 also occurred due to breathing activities carried out by humans in the room.

The average concentration of eight hours of CO_2 in both labs has increased significantly to exceed the quality standards in force in Indonesia, with values reaching 2018 ppm and 2340 ppm. The concentration of CO_2 in the Lab depends on several factors, including the number of humans in the room, the type of human activity, the length of time in the Lab, the density of occupants, and the rate of air exchange (ventilation rate). The average concentration of CO_2 in Lab I and II, which increased when there was human activity due to the condition of windows and doors that were closed during the practicum, causing a low rate of air exchange. It is also caused by the density of occupants of Lab I and Lab II that exceed the standards (the American Society of Heating, Refrigerating, and Air Conditioning Engineer Inc., ASHRAE) for a room/laboratory in a university that cannot exceed 0.25 people/m^2 [15]. The density of occupants Lab I and Lab II is 0.33 people/m^2 and 0.60 people/m^2. Different from the concentration of CO_2 that exceeds the quality standard, the O2 concentration in both rooms when there is human activity still meets the quality standard of 19.9%, but both O2 concentrations have decreased. The average concentration per 24-hour $PM_{2.5}$ in Lab I and Lab II when there is human activity is 23 μgm^{-3} and 43 μgm^{-3}.

In $PM_{2.5}$ concentrations, there is no significant change, whether there is a practicum or not. $PM_{2.5}$ concentrations in the room when there is a practicum still follows the pattern of outdoor $PM_{2.5}$ concentration (TNB). It could indicate the primary source of $PM_{2.5}$ in both labs when there is no human activity or when there is a human activity also coming from outdoor $PM_{2.5}$ that enters both labs. Other research suggested that human activity inside a room is giving off PM_{10} rather than $PM_{2.5}$ [16]. Other than that, $PM_{2.5}$ concentrations in Lab I still meets the quality standard while $PM_{2.5}$ concentrations in Lab II have exceeded the quality standard.

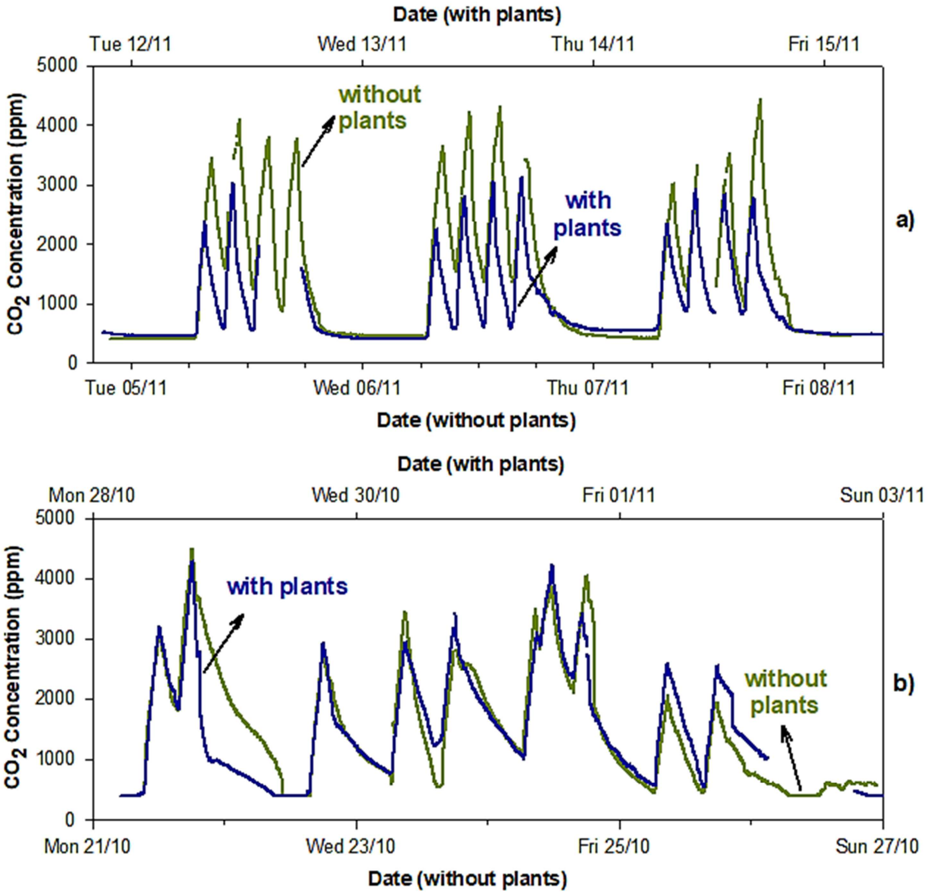

Fig. 8 CO_2 concentration reduction in a) Lab I and b) Lab II

C. *Plant Treatment Effect on IAQ*

The measurement result shows a significant increase in CO_2 concentration when practicum is being conducted (human activities/intervention) in Lab I and Lab II. In this situation, the third condition was given as an effort to decrease the CO_2 concentration (by putting 10 plants pots (*Dieffenbachia sp.*) inside each Lab). Although is not the most effective plant in CO_2 reduction (in CO_2 reduction/hour) [17], *Dieffenbachia sp.* is one of the most frequently used as indoor ornamental plant and was the ones that is accessible at the time of this research. As their effort to sustain life, plants will use some amount of CO_2 as the fuel for them to do photosynthesis – in exchange of O_2 [18]. As a result, decreasing CO_2 concentration and increasing O_2 concentration. As proof of the hypothesis, we also refer to other research that proved the impact of plants decreasing indoor CO_2 concentration. The research stated that putting plants inside an indoor space impacted CO_2 concentration and that there is a significant influence of light intensity (measured in Lux) to CO_2 reduction magnitude inside an indoor space. By this statement, the IAQ measurement on the third condition is conducted using light intensity measurement.

Fig. 8 (a and b) show that there are differences in CO_2 concentration between the second and third conditions of measurement. In Figure 6.b, we can see that quantitatively; there is no significant CO_2 concentration reduction in Lab II. Meanwhile, in Figure 6.a, we can see that there is a significant CO_2 concentration reduction in Lab I. This phenomenon is caused by the difference in lighting conditions when the measurement is being conducted. The average light intensities measured are 18 lux and 281 lux with a maximum value of 80 lux and 643 lux in Lab I and Lab II, respectively. These differences in light intensities are the cause of different photosynthesize activities on the plants inside these labs. Thus, the minimum percentage of CO_2 reduction in Lab I is 34,4%; meanwhile, the maximum percentage of CO_2 reduction is 56,4%.

IV. CONCLUSIONS

In this research, we found that $PM_{2.5}$ concentrations inside the sampling sites, either with or without human intervention involved, tend to follow the trend of outdoor $PM_{2.5}$ concentrations. Due to the urban location, indoor $PM_{2.5}$ concentrations are more often to exceed the 24-hour quality standard given. Meanwhile, indoor CO_2 concentration without human intervention involved follows the trend of outdoor CO_2 concentration and is still below the standard quality limit of CO_2 concentration. However, with human intervention involved, when the sampling sites are filled with around 50 people, the indoor CO_2 concentration is significantly increased way exceeding the standard quality given. On the other hand, indoor O_2 concentration is always inside the bracket of standard quality given, although it is influenced by indoor CO_2 concentration in inverse comparison.

The plant treatment given to each sampling site partially affect reducing indoor CO_2 concentration. This effect is substantially shown where the CO_2 reduction is up to 56,4% in the Lab I. Meanwhile, in Lab II, there was no significant reduction in CO_2 concentration. It is due to the significant difference in light intensity that these labs have.

In conclusion to all of that, we proved that humans (especially ones who lived in urban/rural densely populated areas) could benefit the information given by the technology of low-cost sensors in air quality monitoring device(s). Combined with IoT technology, humans can easily access the data given by the device. Not only giving the sense of assurance for the air they breathe in, but having an air quality monitoring device could also be a way of living a better and healthier life.

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