Response of low-cost environmental monitors to typical emission events in daycare centers

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Abstract. Daycare centers (DCCs), the first program for the social development of young children (0-5 years old), are the most important place for young children besides their homes. Continuous indoor air quality (IAQ) monitoring in DCCs is a means to assess the IAQ and assure a healthy and comfortable environment for infants and toddlers. To date, an extensive array of low-cost air quality monitors (LCMs) is available on the commercial market. Still, only a limited number of these LCMs have been subjected to any research-based evaluation. Furthermore, performance evaluations of low-cost sensors in previous literature are mainly focused on residential emission activities. To the best of our knowledge, there is no research into simulating emission sources related to DCCs scenarios yet. Therefore, this study is aimed to evaluate the response of one type of LCM (2 units) to typical emissions events related to DCCs in detecting the IAQ parameters, that is, particulate matter (PM2.5, PM10), carbon dioxide (CO2), total volatile organic compounds (TVOC), temperature (T), and relative humidity (RH). The LCMs were compared to outcomes from research-grade instruments (RGIs). All the experiments were performed in a climate chamber, where 3 kinds of typical activities (Background test; Arts-and-crafts events; Cleaning events; in a total of 20 events) were simulated by recruited subjects in an indoor climate condition ([20±1 °C & 40±5% RH]). The IAQ parameters sensed by the LCM detected the majority of events, despite a difference in the magnitude of responses. Intra-sensor consistency was significantly strong for all IAQ parameters, with a mean coefficient of variation of 4.14%. The LCM particle sensor underestimated the reference concentrations, with a mean RMSE of 12.8 μg/m^3 for PM2.5 and 36.5 μg/m^3 for PM10. Although TVOC and CO2 sensors reported a weak quantitative response, both had a close correlation with RGIs' data, with R2 values in the range of 0.8-1.0 and 0.5-1.0, respectively. A good qualitative and quantitative agreement was observed in both T (within 1.1°C) and RH sensor (within 1%). In summary, this study reveals that the LCMs investigated are useful in providing IAQ-based monitoring in the specific application scenarios of daycare centers.

Keywords. Indoor air quality, Daycare center, Monitoring, Low-cost monitor
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1. Introduction

Nowadays, a majority of young children around the world attend daycare centers (DCCs). This is an educational project before entry into the compulsory schooling system [1]. In the Netherlands, young children (generally aged 0-4 years old) spend most of their time at DCCs (up to 10 hours per day, 5 days per week, mostly indoors) [2]. Significant space-related contaminants, including diapers, arts-and-crafts supplies, cleaning agents, etc., can be present in DCCs. These typical emission sources result in such spaces being classified as Air Class 2 in ASHRAE 62.1 [3]. Considering the not-fully-developing organ systems of early life, ensuring a healthy indoor environment is of utmost importance to support the well-being of infants and children, as well as staff, in daycare centers.

Over the past two decades, remarkable advances in environmental sensor technologies have enabled the deployment and applications of low-cost air quality sensors for real-time and continuous indoor air quality (IAQ) monitoring and management [4]. Specifically, technological improvements in light scattering for the measurement of particulate matters [5], metal oxide semiconductor (MOS) sensors for the detection of various gases [6], and photoacoustic spectroscopy (PAS) and non-dispersive infrared (NDIR) based systems for the monitoring of carbon dioxide [7] allowed the development of low-cost air quality monitors (LCMs). Consequently, a large array of LCMs are available on the current commercial market, but very few of these monitors have been subjected to any research-based evaluation or data quality certificate. These LCMs normally integrate multiple sensors into one device, including temperature, relative humidity, particulate matters, carbon dioxide, total volatile organic compounds sensors, etc [8].

The recent existing literature on the performance evaluation of low-cost sensors and monitors is mainly focused on particulate matter compared to a reference instrument [9, 10], but very few studies examined other IAQ parameters, especially the TVOC and CO_2 parameters [8]. Additionally, the application scenarios where the low-cost sensors were tested and analyzed are primarily focused on residential emission activities [9-11]. To the best of our knowledge, there is no research into testing the response of LCMs to typical emission sources in daycare centers scenarios yet.

Therefore, in this paper, we present results fromone LCM which has not been tested in previous scientific literature and can detect multiple IAQ parameters, that is, $PM_{2.5}$, PM_{10}, CO_2, TVOC, T, and RH. It is part of a larger and more extensive research where multiple LCMs have been tested for application in DCCs. The research question we seek to answer in this paper is whether this specific LCM is able to reliably monitor IAQ performance in DCCs, given their specific exposure conditions.

2. Research Methods

Three typical main kinds of indoor emissions events related to the DCCs were simulated in a dedicated climate chamber. Performance comparison between the LCM and research-grade instruments (RGIs) was carried out under a typical climate condition: cool & dry.

2.1 climate chamber setup

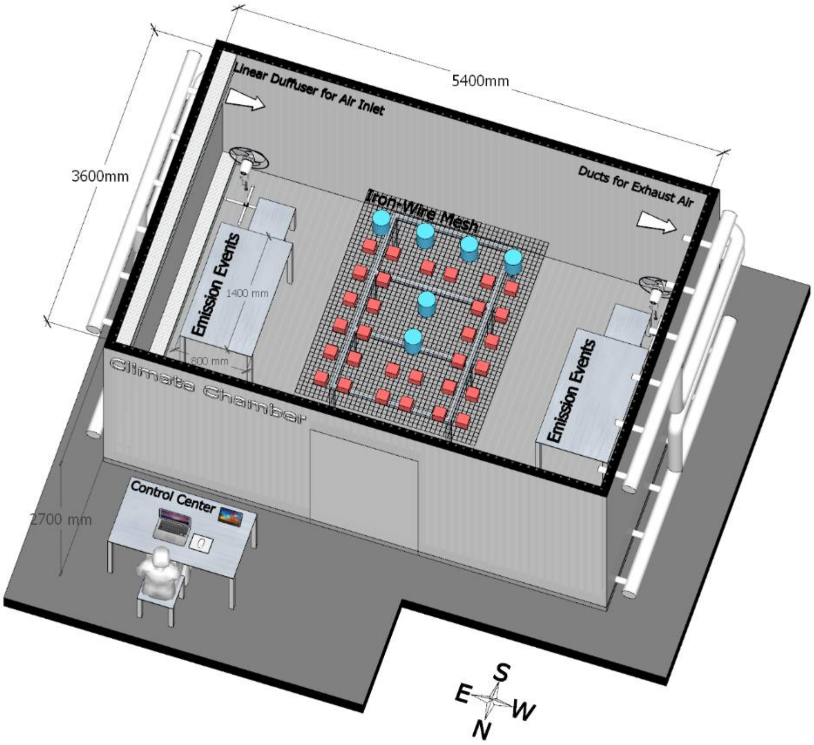

Fig. 1 - An interior axonometric view of the climate chamber set-up.

The experiments were performed in a 52.5 m^3 (W*L*H=3.6×5.4×2.7 m) climate chamber at the Eindhoven University of Technology, the Netherlands. An interior axonometric view of the measurement set-up in the climate chamber is shown in **Fig. 1**. Indoor environmental conditions, that is, temperature, relative humidity, and air exchange rate, are controlled by a dedicated HVAC unit via a proprietary software (LabVIEW2015, BPSCC, version 1.0) in a computer system (outside the chamber, see **Fig. 1**) with data acquisition and storage of historical records. The fresh outdoor air is supplied to the chamber through a 2-stages media filter, i.e., firstly using a coarse air filter, and then a HEPA box air filter (H13-Class with average performance efficiency up to 99.95% for larger than 0.3 μm particles according to EN779:2012). In order to minimize any emissions other than from the primary simulated events, the chamber was furnished with only four stainless-steel chairs, two stainless-steel tables (W*L*H=0.7x1.4x0.9 m), an iron-wire mesh table (W*L*H=2x2.5x0.9m), and four pedestal mechanical fans, as well as the instrumentation of LCMs and RGIs (**Fig. 1**). The iron-wire mesh panel setting is aimed to allow sufficient airflow to go along the sensors. Four mechanical fans were operated and pointed, respectively, towards interior surfaces (north and south wall) during the whole experiment, to ensure the homogeneous distribution of indoor air. Also, prior to the first experiment, a thorough cleaning and thermal treatment of the chamber interior were performed to remove all reactive compounds. All the LCMs and RGIs are co-located on the iron-wire mesh table in the center of the climate chamber during the experiments and kept at least one-meter distance away from the emission sources.

2.2 selection and simulation of the typical IAQ emission sources in DCCs

The selection of simulated activities was based on the discussions and interviews with managers and pedagogical staff in two Dutch daycare centers during a preliminary field survey. Ultimately, considering the frequent occurrence in DCCs, three types of emissions activities were selected, that is, arts-and-crafts activities (4 art-painting tests, 4 plasticine-modeling tests, 4 gluing tests), cleaning activities (2 table-cleaning tests, 1 vacuum-cleaning test), and background activities (4 tests with subjects, 1 test without subjects). Briefly, four subjects were given one set of material-kit and performed each arts-and-crafts event test for one hour inside the chamber; two subjects use disinfectants or vacuum cleaners to perform clean activities; for the background test, four subjects sat inside the chamber and did reading work, except for one background test without any subject.

Regarding the experimental procedure, the first step is to ventilate the chamber room at the maximum rate (6.84/h) for at least 60 minutes to ensure indoor air quality comparable to outside conditions before the experiments. Then, the ventilation system was turned off, but an additional evaporative humidifier and two dehumidifiers with the filters removed were still kept working to make temperature and relative humidity achieve the desired values (20±1 ℃ & 40±10 ℃)). Once the equilibrium was achieved, four or two volunteers would enter the chamber. The subjects wore identical new lab coats and filter masks (OSHA & NIOSH N95 rating, Model 8210, 3MTM) and did not use any fragrance personal care products after taking a shower one night prior to the experiment to minimize any emissions from the researchers. After 10 min, they performed prescribed activities for a period of 60 min. This 60-min activity is indicated as one event test. After that, the subject exited the chamber, and at the same time, the ventilation system was turned on again to exhaust all of the pollutants. The next experiment was conducted when the values of contaminants (CO_2, PM, and TVOC) in the research-grade instruments showed background levels as before the emission events.

2.3 low-cost air quality monitors

Results from the AI-2003W (Edimax Technology Co., Ltd, Taipei City, Taiwan) are presented in this paper for the cool & dry conditions [20±1 ℃& 40±10% ℃]. This LCM was selected due to the fact that it measures multiple IAQ parameters, that is, $PM_{2.5}$, PM_{10}, CO_2, TVOC, T, RH, and formaldehyde (HCHO). Its specifications are shown in **Tab. 1**. This monitor has not been tested in previous research. Two units of AI-2003W were purchased in the Netherlands in February of 2021. The two units take measurements at 5-min intervals.

Tab. 1 – manufacturer specifications for the Edimax AI-2003W.

Parameter	Sensor	Accuracy	Range
T	Sensirion SHT30	±1°C	0-80 °C
RH	Sensirion SHT30	±5%	0-100%
$PM_{2.5}$	Plantower PMS5003	±20% at 100-500 μg/m^3; ±15μg/m^3 at 0-100 μg/m^3	0-500 μg/m^3; 0.3-2.5μm
PM_{10}	Plantower PMS5003	-	0-500 μg/m^3; 0.3-10μm
CO_2	Sensirion SCD30	±30ppm	0-5,000 ppm
TVOC	Sensirion SGP30	±15%	0-1,000 ppb
HCHO[a]	Winsen ZE08-CH2O	±10%	0-1 mg/m^3

[a] Has the ability to detect HCHO, which was not tested and analyzed in this study.

2.4 research-grade instruments

For reference monitoring of time-resolved and size-resolved particulate matters level, Grimm Aerosol Spectrometer Model 11-D (abbreviated here as Grimm 11-D) detects the particles in 31 equidistant size channels from 0.253 to 35.15 μm. Three Grimm 11-D spectrometers were successfully calibrated with NIST certified PSL particles, and the calibration was verified on November 23rd, 2020, in GRIMM Aerosol Technik. Grimm 11-D measures particle mass concentration via light scattering technique and measures at an interval of 6 seconds. Grimm 11-D can output mass levels and the particle counts concentrations for all size channels. Although both are not regulatory-grade particles monitors, their portability and affordability, as well as high reliability, have made them widely used in previous and recent air-quality-related scientific research studies [12, 13].

A Photoacoustic Gas Monitor (INNOVA 1512, LumaSense Technologies A/S, Ballerup, Denmark) coupled with a Multipoint Sampler and Doser (INNOVA 1403, LumaSense Technologies A/S, Ballerup, Denmark) was used for the reference measurement of CO_2 gas. It was factory calibrated and compensated for temperature, pressure fluctuations, and water vapor by the manufacturer on December 21st, 2020, to ensure accuracy of the measurement within 1.5% of the gas concentration. The detection limits given by the calibration chart of the manufacturer were 1.5 ppm for CO_2 and 0.006 ppm for SF_6. Five sampling points (four at the corners and one at the center of the sensor table) and one tracer-gas dosing point (in the bottom air inlet of the climate chamber) were selected. Those sampling and dosing points were connected by AISI-316 stainless steel polytetrafluoroethylene (PTFE) tubes to the respective channels on the devices of INNOVA 1403. The air was continuously and consecutively sampled from the five sampling points and analyzed at a ca. 42-second interval for each point. One measuring cycle lasted for ca. 3.5 minutes. We integrated the data of five sampling points into one INNOVA dataset after confirming the full mixing of the air inside the chamber. The INNOVA data were averaged at 5-min intervals.

As mentioned in a recent research article [8], there is no true reference instrument for monitoring time-resolved TVOCs due to limitations in the current technologies. Two Aeroqual Photoionization Detectors with a photon energy of 10.6 electron Volts (Aeroqual, Series 500 IAQ, Aeroqual Ltd., Auckland, New Zealand) were used as the research-grade TVOC measurement instrument. On December 17th, 2020, the two Aeroqual instruments were factory calibrated against a certified mixture of isobutene in synthetic air diluted with zero air using mass flow controllers with calibrations traceable to the National Institute of Standards and Technology (NIST). The Aeroqual has a working range of 0.01-30 ppm and accuracy of ±10%, storing data every minute.

For reference monitoring of room temperature and relative humidity, we deployed an EE08 series transmitter (E+E Elektronik® Ges.m.b.H., Engenwitzdorf, Austria) with a data logger (Squirrel 2040, Grant Instruments Ltd., Cambridge, UK) set at a 1-minute interval. The EE08 series is equipped with an NTC thermistor with interchangeable curves (Ø2.4mm) in the working range of -55 to +80℃, and reported accuracy of ±0.05℃ from 0-50℃, and contains an HC101 high-end humidity sensor with a range of 0-100% RH and a factory accuracy of ±2% at 0-90% RH, ±3% at 90-100% RH.

2.5 data analysis and statistical methods

To understand the overall performance of the monitor, focus was put on two aspects: 1) Consistency; 2) Event detection. The first part is to compare the precision of the two units, which was characterized by two metrics: standard deviation and coefficient of variation (CV). In the second part, we computed the linear regression of each unit's and research-grade instrument data, where the coefficient of determination (R^2), slope, and intercept were calculated and compared. Also, the root mean square error, and the normalized root mean square error were used to help understand the error associated with each sensor measurement when compared with the research-grade instruments. All the aforementioned metrics and corresponding equations were suggested to evaluate the performance of low-cost sensors by U.S. EPA [14]. All the data processing and analysis were done by using python 3.8.

3. Results

3.1 Consistency

Tab. 2 and **Tab. 3** represent the results of the consistency (SD and CV) between the two similar LCM units in detecting all the IAQ parameters, that is, $PM_{2.5}$, PM_{10}, CO_2, TVOC, T, and RH. Lower SD and CV values mean better precision and less variation in trends. Considering the limit of paper pages, only the maximum, average, and minimum of SD and CV among 20 event tests are summarised in the table. Overall, for all the IAQ parameter-sensors tested in 20 events, the mean of SD is in the range of 0.1-13.8 (with specific unit) and the mean of CV is in the range of 0.31-10.53%, which exhibits strong consistency and supports the use of comparison for analysis. Specifically, when it comes to the CV metric, the temperature sensors showed the best precision among all the IAQ-parameter sensors, which reported 0.06-0.74% precision under 20 event tests. Also, the RH sensor and CO_2 sensors showed very good consistency with the CV in the range of 0.64-1.35% and 0.55-1.62%, respectively. It should be mentioned that $PM_{2.5}$ and PM_{10} sensors reported zero SD and CV values in some tests due to the very low emissions concentrations in these tests. In this case, all the output of sensors were close to the lower detection limit.

Tab. 2 – Standard deviation (SD) for different parameters between two similar LCM units under 20 tests.

Test	$PM_{2.5}$	PM_{10}	CO_2	tVOC	T	RH
Max	4.3	2.5	21.2	30.9	0.1	0.6
Mean	0.4	0.3	13.8	5.5	0.1	0.4
Min	0	0	2.6	1.7	0	0.3

Notes: the unit of $PM_{2.5}$ and PM_{10} is μg/m^3; the unit of CO is ppm; the unit of tVOC is ppb; the unit of T is °C; the unit of RH is %.

Tab. 3 – Coefficient of variation (CV) for different parameters between two similar LCM units under 20 tests (values in %).

Test	$PM_{2.5}$	PM_{10}	CO_2	tVOC	T	RH
Max	61.12	57.10	1.62	4.88	0.74	1.35
Mean	9.12	10.53	1.17	2.78	0.32	0.93
Min	0	0	0.55	0.93	0.06	0.64

3.2 Event detection

Fig. 2 shows the typical response of the two LCM units and research-grade instruments to 5 typical emissions events related to daycare centers, as illustrated by the time-series plot of the sensor logging. The highlighted region of each plot is the 60-min event test period. Correspondingly, **Fig. 3** shows the scatter plots and linear regression between RGIs and each unit, with slopes, intercept and R^2 for each 60-min event test. We describe the components of **Fig. 2** and **Fig. 3** in parallel by following the response of the sensed parameters, from $PM_{2.5}$, PM_{10}, CO_2, TVOC, T, to RH, to each event, from "Background test", "Gluing", "Painting", "Table cleaning", to "Vacuum cleaning".

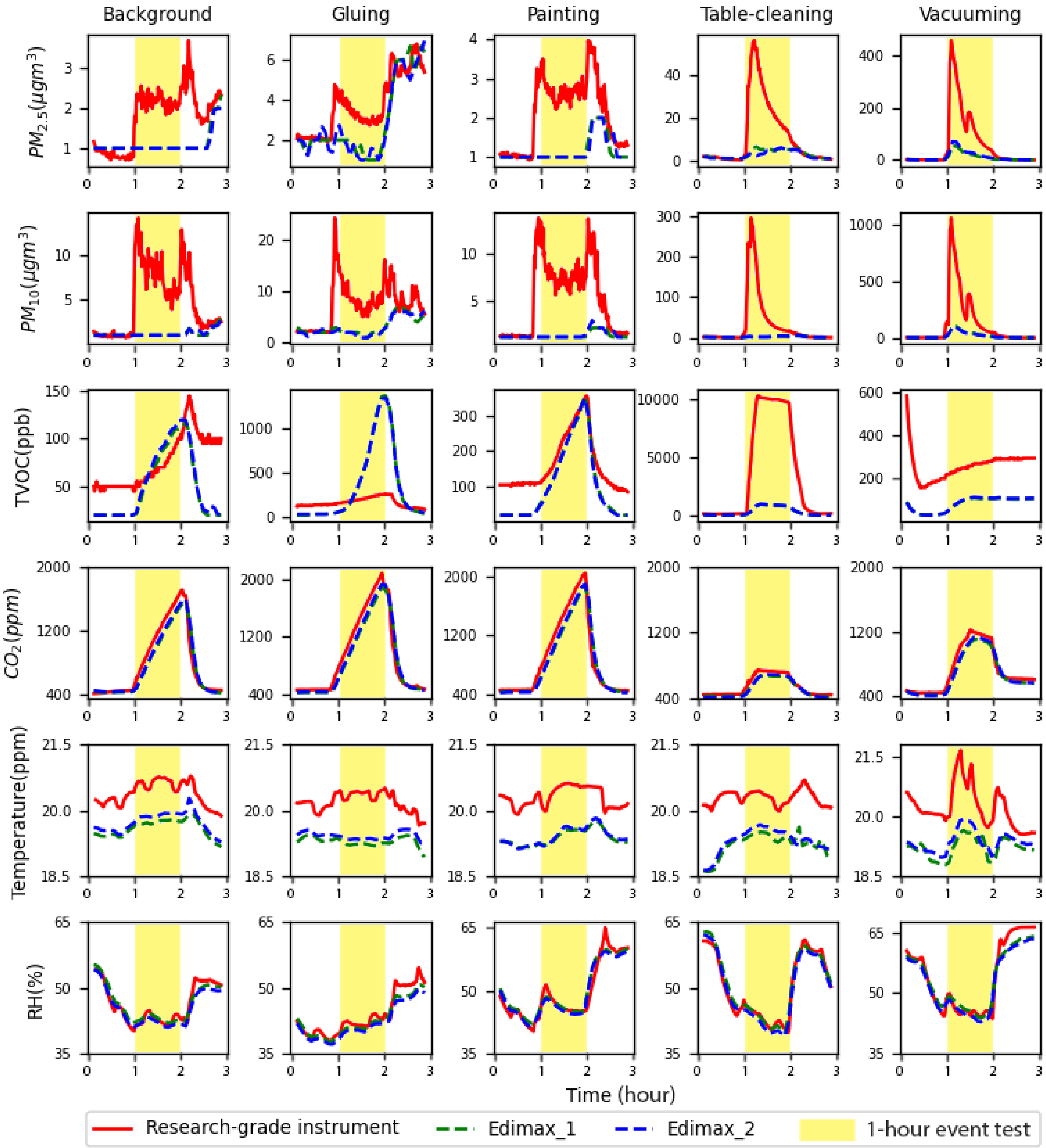

Fig. 2 – Time series plots of LCM and RGIs during Background test, Gluing, Painting, Table-cleaning, and Vacuuming events (the highlight region of the plot refers to the 60-min event test period).

In the first and second rows of **Fig. 2** and **Fig. 3**, $PM_{2.5}$ and PM_{10} sensors are compared with RGI (Grimm 11-D). When it comes to the Background test, during which four volunteers sat still inside the chamber and did reading work, the LCM $PM_{2.5}$ and PM_{10} sensors did not detect the event while the RGI (Grimm 11-D) monitored the variations in $PM_{2.5}$ concentrations from 0 to 3 μg/m^3, PM10 concentrations from 1 to 10 μg/m^3. Consequently, linear regression cannot be made during these two tests. During one of the arts-and-crafts events (Gluing), two units reported particle variations in $PM_{2.5}$ and PM_{10} and followed the trends similar to RGI (Grimm), with the correlation for $PM_{2.5}$: R_1=0.65, R_2=0.61; for PM_{10}: R_1=0.38, R_2=0.81, despite much lower mass concentrations emissions. Both under-reported the particle reference concentrations with a RMSE of 1.8 μg/m^3, and a NRMSE of 55.7% for

$PM_{2.5}$; with a RMSE of 7.0 μg/m³ and a NRMSE of 82.1% for PM_{10}. However, similar to the Background test, both LCM units did not detect another arts-and-crafts event (Painting). In the cleaning activities (Table-cleaning and Vacuuming), both units reported slight variations while the RGI (Grimm) detected significant particle emissions concentrations in $PM_{2.5}$ and PM_{10}. Both units displayed weak quantitative response in Table-cleaning and Vacuuming, with a RMSE of 27.1 and 167.3 μg/m³ and a NRMSE of 97.5% and 105.1% for $PM_{2.5}$; with a RMSE of 114.9 and 370.1μg/m³ and a NRMSE of 137.9% and 121.2% for PM_{10}, respectively. When compared to the RGI (Grimm 11-D), good correlations for the two units were found in the Vacuum-cleaning event (for $PM_{2.5}$: R_1=0.59, R_2=0.66; for PM_{10}: R_1=0.58, R_2=0.66). Besides, both LCM units showed the ability to return to background levels after the emissions events.

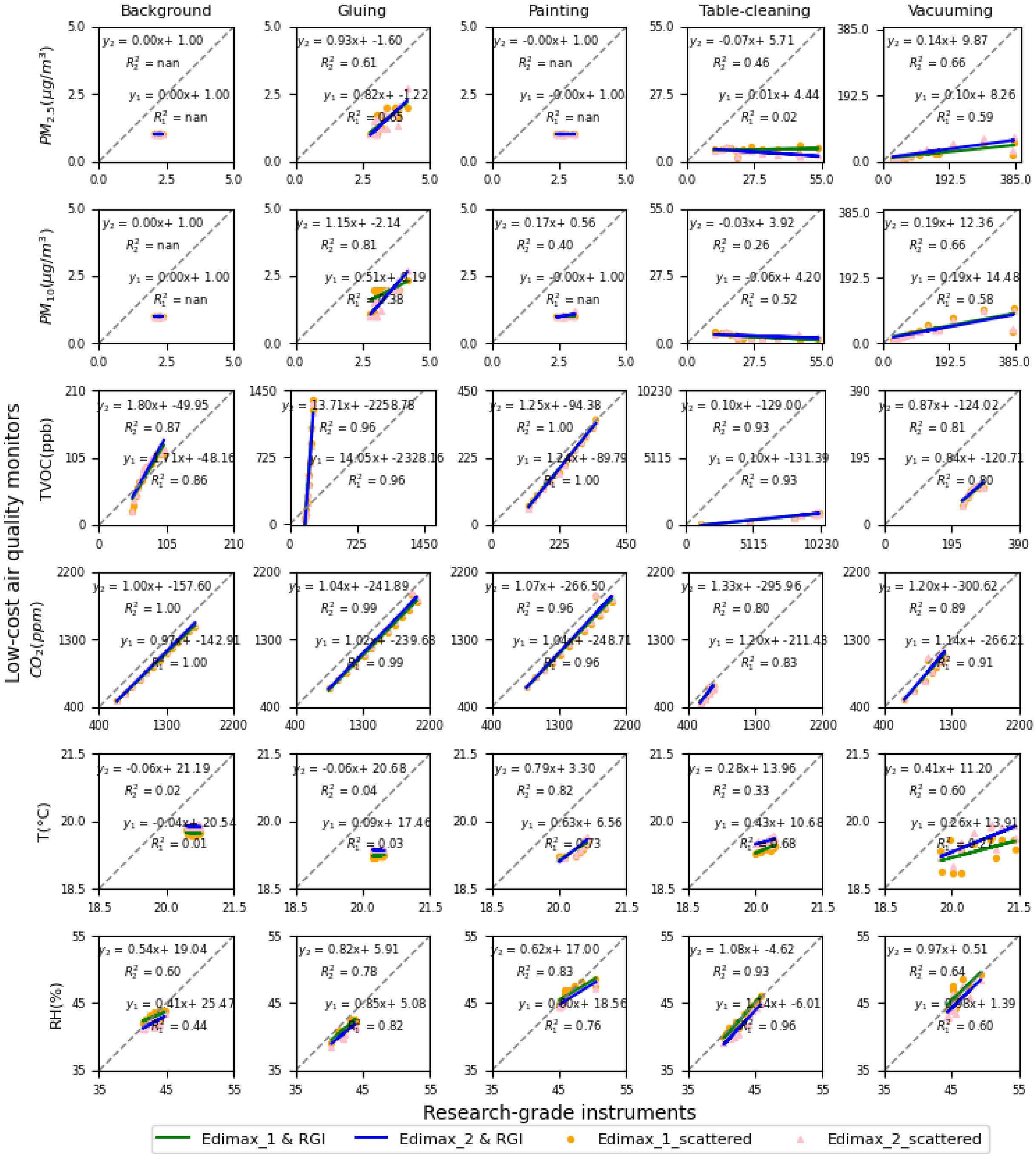

Fig. 3 – Scatter plots and linear regression of each unit with RGIs during Background test, Gluing, Painting, Table-cleaning, and Vacuuming events.

The third row of **Fig. 2** and **Fig. 3** presents the TVOC sensors comparison with RGI (Aeroqual-PID). Both LCM units detected all events, followed the consistent trends with the RGI (Aeroqual-PID), and showed a close correlation (R^2 in the range of 0.8-1.0). But the quantitative response varied up to 11 times depending on the emissions events, with a RMSE in the range of 16 to 8274 ppb, and a NRMSE in the range of 23.0 to 257.3% when compared to the RGI (Aeroqual-PID).

In the fourth row of **Fig. 2** and **Fig. 3**, the CO_2 sensors are compared with RGI (Innova). It shows that the two units and RGI (Innova) were very closely correlated in their response to the CO_2 emissions events (R^2 in the range of 0.8-1.0). Considering the whole period of the 5 event tests, the LCM CO_2 sensors under-reported the reference CO_2 levels with a RMSE in the range of 74 to 199 ppm, and a NRMSE in the range of 10.6% to 14.2%.

In the fifth row of **Fig. 2** and **Fig. 3**, the air temperature sensors comparison with RGI (EE08) is shown. Throughout 20 events (under cool and dry conditions), the two LCM units detected the temperature variations despite a relatively narrow temperature span (19.8-21.4°C, mean=20.5°C) as registered by the RGI. unit 1 and unit 2 under-reported the air temperature on average by 1.1°C and 1.0°C, respectively, during the overall duration of these 20 events.

In the sixth row of **Fig. 2** and **Fig. 3**, the RH sensors are compared with RGI (EE08). Similar to temperature, the RH sensors displayed a consistent dynamic response to RH variations even though variations were limited (37-50%, mean=43%) during the 20 events.

4. Discussion

The precision (SD and CV) acquired in the event tests related to daycare centers revealed a significantly reliable consistency of two identical units of a low-cost air quality monitor in detecting the IAQ-parameters, that is, $PM_{2.5}$, PM_{10}, CO_2, TVOC, T, and RH. A similar outcome was obtained by Moreno-Rangel et al. [15], which assessed and compared five Foobot low-cost air quality monitors and research-grade instruments in measuring residential emissions events. Their results showed a very strong uniformity and low variability among five units in detecting IAQ-parameters including $PM_{2.5}$, CO_2, TVOC, T, and RH.

Regarding the performance of particle sensors, both units under-reported $PM_{2.5}$ and PM_{10} concentrations when compared to reference instruments for all events tested in this study. This aligns with the study of Zou et al. [16]; Also, in the study of Demanega et al. [8], which examined 8 LCMs and 8 low-cost single sensors in detecting residential PM_1, $PM_{2.5}$, PM_{10}, CO_2, TVOC, T, and RH, stated that the majority of tested devices underestimated reference values by up to 50%. The sensors showed the ability to return to baseline concentration after an event related to the daycare center. This was also found for residential events [16, 17]. In particular, it was shown that the qualitative and quantitative agreement varied depending on the emissions events, possibly because of the different particle composition, size distribution, and optical properties under certain events [17]. Besides, the differences might be caused by the limited detection bins of light scattering sensors [11, 18]. In general, the two LCM unit $PM_{2.5}$ sensors reported a mean RMSE of 12.8 μg/m^3 under 20 events tested in this study, which met the original equipment manufacturer (OEM) specification (±15μg/m^3), as outlined in **Tab. 1**.

In this study, due to the currently limited detection technology, we utilized the PID-based VOC instruments as a reference device, which could provide high temporal resolution and agreeable results of air monitoring, but were stated not as robust and accurate as a flame ionization detector (FID) [19]. The two units and RGI (Aeroqual-PID) displayed a different sensitivity toward the different events. The reason might be caused by the intrinsic properties of the devices [19, 20].

As reported in the study [8, 15], the results reported from the two LCM CO_2 sensors in this study re-confirmed that the non-dispersive infrared (NDIR) technology can result in measurable qualitative responses to all events. The two units do underestimate the reference values. For all 20 events tested in this study, the accuracy of two units produced a RMSE in the range of 25-227ppm (mean=168ppm), which did not meet the OEM specification (±30ppm). Regarding the air temperature and RH sensors, the results showed that both-parameters sensors were strongly correlated with reference measurements and produced quantitative responses to variations, which met the OEM specifications.

Additionally, when it comes to the comparison of the 3 different main events tested in this study, we found that the dominance of pollutants varied per event type. Specifically, in the Background tests, only CO_2 concentrations caused by the presence of occupants were dominant; in the arts-and-crafts events, TVOC concentrations, as well as CO_2 levels, became significant. Particularly, in the cleaning activities, PM concentrations were significantly dominant, in addition to CO_2 and TVOC levels.

Some limitations in this study design should be mentioned here. First, only the measurement performance aspect of the LCM was evaluated and compared, not the utility, portability, and cost. The particle reference instrument (Grimm 11-D) is an optical-based instrument. During the measurement, the density of the particle was not calibrated by the gravimetric-based source-specific measurement due to the constraints of the devices available. Instead, it was set in the device as 1.68 g/cm^3. Similarly, the TVOC reference (Aeroqual-PID) is not a reference instrument designated by national accreditation bodies.

5. Conclusions

The experimental design of this study is aimed to evaluate the response of one type of low-cost air quality monitor (2 units) to 3 kinds of typical emissions events in the application scenario of a daycare center in detecting IAQ parameters ($PM_{2.5}$, PM_{10}, CO_2, TVOC, T, and RH). To summarize, the LCM displayed large variability as indicated by performance metrics suggested by U.S. EPA, including precision, bias, linearity, and error. The IAQ-parameters sensors, however, detected the majority of events simulated for the application scenarios in daycare centers, despite the different degree magnitude of response. This means that not for each IAQ parameter the absolute values can be trusted, but the LCM investigated is able to detect events, which could trigger mitigation actions to correct the situation.

6. Acknowledgment

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Data Statement

The datasets generated during and/or analysed during the current study are not available because part of data is still being involved in another project un-published, but the authors will make every reasonable effort to publish them in near future.