Chemical Insights

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TECHNICAL REPORT

Impact of 3D Printing on Indoor Air Quality in a University Maker Center

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Table of Contents

List of Figures

List of Tables

Introduction

3D printers have been widely used in educational settings from K-12 schools to universities.[1,2] They are placed in various locations and environmental settings on campus, such as classrooms, maker centers, laboratories, offices, and used for teaching, research, design and prototyping in engineering and architecture, and other fields. Particularly, maker centers in universities can house diverse types and multiple 3D printers in one center, which are accessible to teachers and students on campuses, and they can be in constant operation.

Chemical Insights Research Institute (CIRI) of UL Research Institutes has conducted a multi-year research initiative on 3D printer emissions and has found that 3D printing results in ultrafine particle (UFP, smaller than 100 nm) and volatile organic compound (VOC) emissions.[3,4] When inhaled, small particles have the tendency to penetrate deep into the lungs and even the bloodstream, which can be associated with respiratory and cardiovascular diseases.[5] Some of the VOCs detected from 3D printer emissions could cause acute or chronic adverse health effects including irritation, respiratory disease, and cancer depending on the dose and exposure conditions.[4]

3D printer use on campus can result in elevated levels of indoor air pollutants, and exposure to these pollutants could raise health concerns, especially to vulnerable people, such as those with respiratory disease and asthma. In this study, we visited a university maker center that is open to all teachers and students and monitored VOC and particle levels in the maker center over time. Data were evaluated to determine how 3D printer use impacts indoor air quality.

Field Study Methods

SAMPLING SITES

There were three environments for air quality measurements: the maker center (hereafter as Maker Center), a classroom (hereafter as Classroom) and an outdoor site (hereafter as Outdoor). The Maker Center houses over 20 desktop fused filament fabrication (FFF) 3D printers, see **Figure 1**. Printing is available using various thermoplastic materials, with PLA (polylactic acid) as the most commonly used. There were also six stereolithography (SLA) 3D printers that use photopolymer resins, in addition to post-processing units for wash and cure treatment. The FFF printers were continuously operating during open hours and overnight, and the SLA printers and post-processing units were occasionally used. In addition, there are four laser cutters that were used continuously. It should be noted that Maker Center was connected to a metal shop with a door that was open occasionally. The classroom was close to Maker Center and was used as a comparison environment that did not house any 3D printers. Lecture classes were conducted normally as scheduled in the classroom, and when it was not available for air testing, sampling was conducted in the hallway. Outdoor ambient air was also monitored as a reference for the indoor air measurements. The site was outside of the building entrance with minimal anthropogenic emission sources.

Figure 1. Inside of Maker Center with 3D printers.

SAMPLING AND ANALYSIS METHODS

Airborne particle concentrations and size distributions were measured in real time with a NanoScan Scanning Mobility Particle Sizer (SMPS) for particles ranging from 10 to 400 nm in diameter. An Optical Particle Sizer (OPS) measured larger particles from 0.3 to 10 μm in size. Dynamic air samples were collected for VOC and aldehyde analyses using portable vacuum pumps with collection onto Tenax sorbent tubes and 2, 4-dinitrophenylhydrazine (DNPH) cartridges separately. The Tenax tubes were analyzed according to the US EPA TO-17 method for C6 – C16 organic chemicals, and DNPH cartridges were analyzed according to the US EPA TO-11A method for low molecular weight aldehydes. Sampling instruments are shown in **Figure 2**. Particle and dynamic VOC/aldehyde sampling was conducted on two separate days during normal usage of Maker Center and Classroom. In addition to a stationary site near the FFF 3D printers, a mobile cart with particle instruments that could be moved to different locations was used to study spatial variations of the air quality within the space. Particle sampling was conducted through the entire monitoring duration, and VOC/aldehyde samples were collected for before, during, and after the normal opening time of Maker Center. Target dynamic sample volumes were 18 L for VOCs and 45 L for aldehydes. Moreover, particle and passive VOC sampling was extended for a week to capture the change of air quality associated with different times and activities in both Maker Center and Classroom. The passive VOC samples were collected via diffusion onto Tenax tubes and analyzed in the same way as dynamic VOC samples.

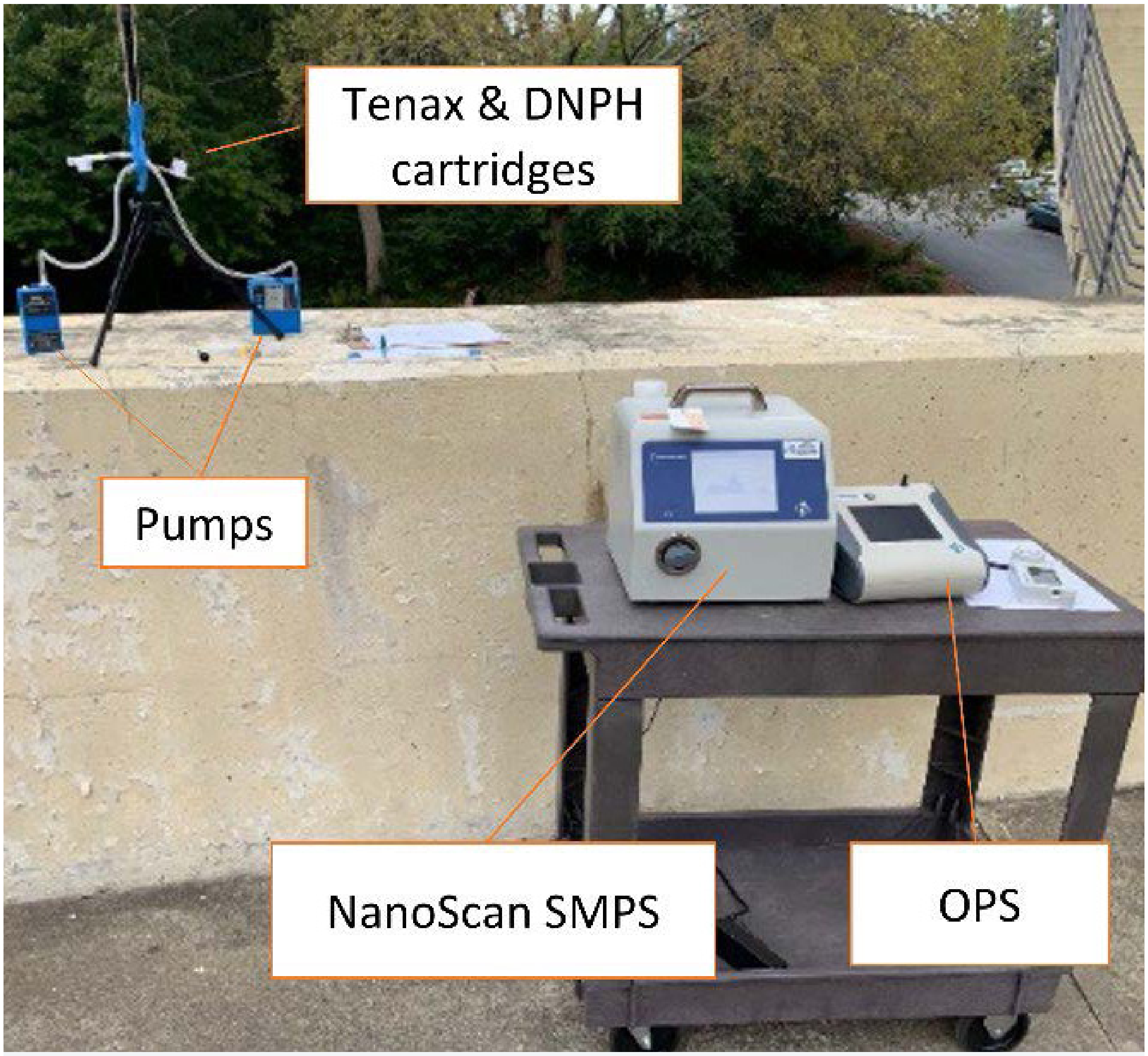

Figure 2. Particle and VOC sampling instruments at the outdoor site.

Results

PARTICLE LEVELS

Overall particle emission characteristics, including number concentration, geometric mean diameter (GMD), and fine particulate matter ($PM_{2.5}$, less than 2.5 µm in size) mass concentration, were calculated for each monitoring site (**Table 1**). Week-long monitor data were used for Maker Center and the adjoining Classroom. Overall, the particle concentration in Maker Center was higher than Classroom, but outdoor levels exceeded the indoor levels. The outdoor sources of particles were not identified. The GMD of particles in different sites were comparable.

TABLE 1: *SUMMARY OF PARTICLE LEVELS AT DIFFERENT MONITORING SITES*

	Maker Center	Classroom	Outdoor
Average concentration (#/cm³)	4.52×10^3	3.15×10^3	1.24×10^4
Maximum concentration (#/cm³)	2.82×10^4	9.55×10^3	1.25×10^5
Average GMD (nm)	60.5	58.5	54.4
Average $PM_{2.5}$ (µg/m³)	4.00	2.06	6.38

Trends in Maker Center and Classroom

Through the week long monitoring, particle concentration trends in Maker Center and Classroom agreed with each other, except for some elevations of particle concentrations in Maker Center (**Figure 3**). During the nighttime period, after 10 PM to before Maker Center was opened at 10 AM, the two NanoScan instruments in Maker Center and Classroom agreed well, due to less or no activities in Maker Center. The measurements were considered background levels. During normal operational hours of Maker Center, OPS concentrations were always higher in Maker Center than those in Classroom. Spikes and elevations shown in Maker Center particle concentrations were associated with activities in Maker Center or near the monitors, which were more frequent during the period when Maker Center was open to public (12 PM to 5 PM). Interestingly, during a 2-day weekend period, there were some spikes in particle concentration in Maker Center resulting from Halloween celebration activities. The maximum concentration in Maker Center was 2.8×10^4 #/cm³, which is about three times higher than that in Classroom.

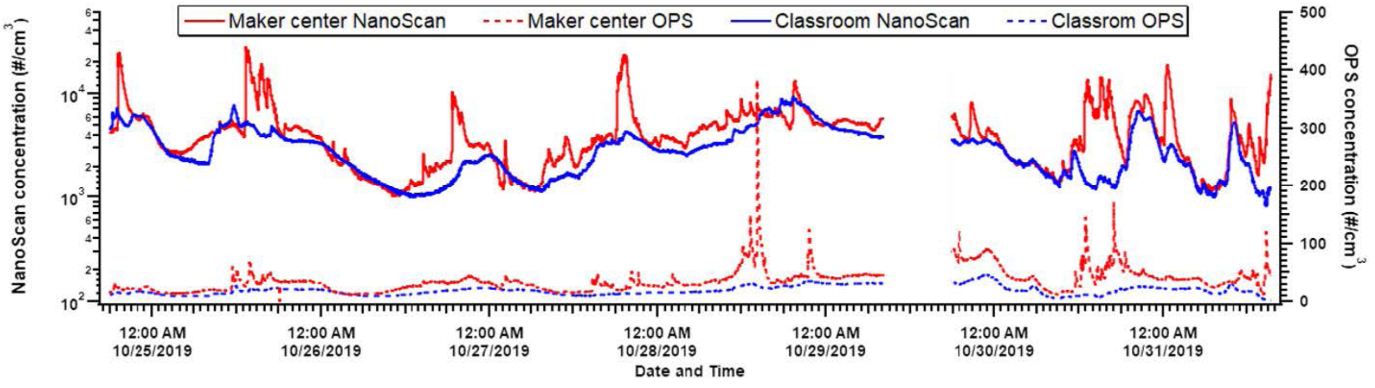

Figure 3. Particle concentrations in Maker center and Classroom during week-long monitoring.

The trend of particle GMD during the week-long monitoring is shown in **Figure 4**. Combining **Figure 3** and **4**, a spike of NanoScan concentration in Maker Center was associated with a drop of particle mean size. This may have been caused by the burst of small particles formed from activities happening in Maker Center, such as 3D printing, which is known to emit mainly ultrafine particles (less than 100 nm in size).[3]

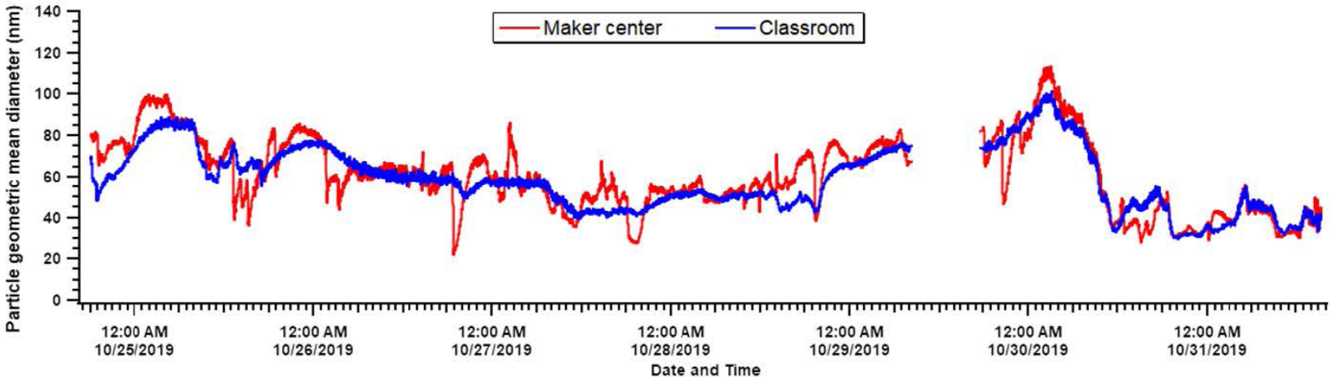

Figure 4. Particle geometric mean diameters in Maker Center and Classroom during week-long monitoring.

Particle Concentrations at Different Locations

The two daily monitoring data are shown in **Figure 5** and **6**. Outdoor particle number concentrations were high and maintained at a relatively constant level of around 10^4 #/cm³. Classroom or hallway particle number concentrations were also stable during the monitoring period with averages ranging from approximately 4000 to 6000 #/cm³, which were normally lower than those in Maker Center.

The stationary NanoScan and OPS in Maker Center were in front of the FFF 3D printers, thus their data reflect the air quality mostly being affected by 3D printing; see the red curves in **Figure 5** and **6**. The mobile cart was located at the opposite side of Maker Center away from the FFF printers for most of the time and was occasionally moved around to different locations where other activities happened. These included: 1) near the sewing machine and the front door area where students sit; 2) near the connection door of the metal shop and where the SLA printers were located; and 3) near the laser cutters at a corner of Maker Center; see blue curves in **Figure 5** and **6**. In general, particle number concentrations followed similar trends for near and far away from the FFF printers, which could be a result of the overall air mixing inside Maker Center. However, more spikes in data were observed from the cart instruments than the stationary instruments, which could be associated with the emissions from activities close to the cart that were not ventilated as quickly as those near the FFF printers. There was additional ventilation near the FFF printer area, which increased air-mixing and likely resulted in consistent concentration trends for the stationary instruments. Elevations of particle concentration were observed near the FFF printers, which could be a result of 3D printing. There were cases when near printer concentrations were higher than away from printers, as well as the opposite. However, the monitoring site near the metal shop tended to constantly show higher particle concentrations than the stationary site. This may be due to the emissions from the metal shop entering into the Maker Center via the slightly open door. Higher particle concentrations near the sewing machine/ student area over the stationary site were also detected, while lower concentrations were detected near the laser cutters.

Estimated $PM_{2.5}$ concentrations from SMPS and OPS data showed Maker Center and Classroom followed similar trends, but Maker Center had about two times higher concentrations than Classroom. The maximum $PM_{2.5}$ concentration in Maker Center reached 31.1 μg/m³, which is about five times higher than that in Classroom, and it is close to the 24-hour $PM_{2.5}$ standard according to U.S. EPA national ambient air quality standard (35 μg/m³).

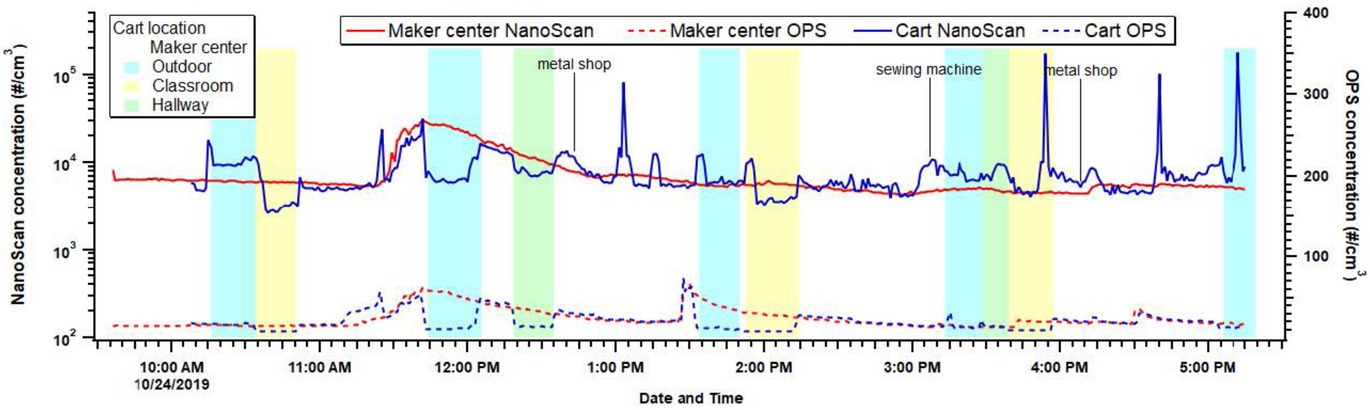

Figure 5. Particle concentrations at different times and locations for October 24. Maker Center instruments were stationary (red); the cart was at the opposite side of Maker Center away from the printers (blue) other than noted (shaded area).

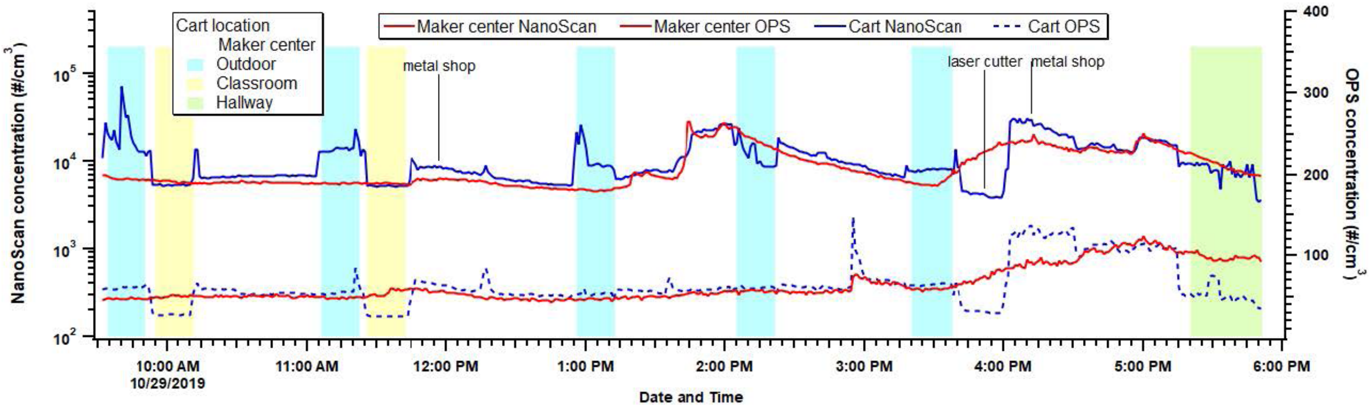

Figure 6. Particle concentrations at different times and locations for October 29. Maker Center instruments were stationary (red); the cart was at the opposite side of Maker Center away from the printers (blue) other than noted (shaded area).

VOC LEVELS

Total VOC

A comparison of total VOC (TVOC) concentrations is shown in **Figure 7** for the two daily monitoring sessions. Indoor TVOC concentrations, both in Maker Center and Classroom, were consistently higher than those outdoors. Normally, TVOC concentrations inside Maker Center were higher than those in Classroom, except for two cases, which were associated with the high occupancy in Classroom during class sessions. Most of the indoor TVOC concentrations ranged from 250 to 400 μg/m³, while the maximum concentration was above 500 μg/m³. According to the U.S. Green Building Council, the Leadership in Energy and Environmental Design (LEED) TVOC recommended limit is 500 μg/m³ for green buildings. In some cases, the TVOC concentrations at far printer locations were higher than near printer locations, while the overall data were comparable for the distinct locations in Maker Center; this is similar to particle concentration trends, which reflected the air-mixing inside Maker Center.

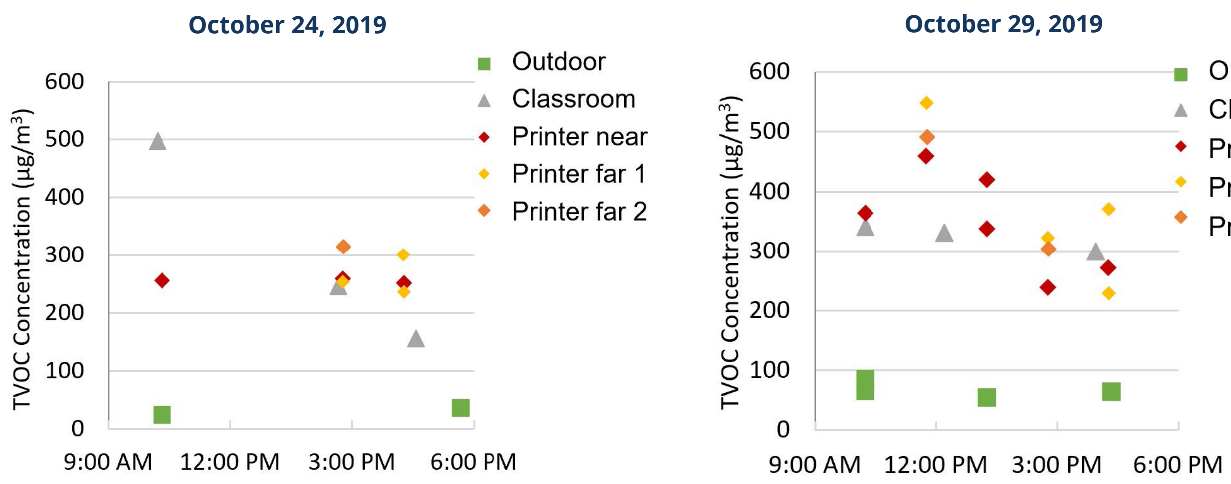

Figure 7. TVOC concentrations at different time and location for October 24 (left) and October 29 (right).

Individual VOC

The two daily dynamic samplings showed similar VOC compositions, see **Table 2** and **3**. The commonly detected VOCs were aldehydes, siloxanes, and aromatic hydrocarbons. Specifically, decamethylcyclopentasiloxane (D5) was found with much higher concentrations indoors than outdoors and higher in Classroom than Maker Center, likely associated with the use of cosmetics and personal care products by occupants.[6] Formaldehyde, toluene, and xylene are ubiquitous in the environment, but with elevated concentrations indoors for both Maker Center and Classroom. In Classroom, higher concentrations of octamethylcyclotetrasiloxane were found compared to Maker Center for both days, which was potentially attributed to plastics, rubber products, and cosmetics. In addition, 2,5-cyclohexadiene-1,4-dione, 2,5-diphenyl- in Classroom (October 29) was found to be much higher than those in Maker Center. Esters like 2-propenoic acid, 2-methyl-, 2-hydroxypropyl ester, and methyl methacrylate were not detected or in low concentrations in Outdoor and Classroom, but with elevated concentrations in Maker Center. Particularly, their concentrations at the Printer Far 2 location were always higher than other locations. This is likely because the Printer Far 2 location was close to the SLA printers that use photopolymer resins containing mainly methacrylate compounds.[7] Other top 15 VOCs that were only detected in Maker Center included tetrahydrofuran (THF), cyclohexanone, and 2-butenal in the October 29 samples, all of which have been detected from 3D printing. In addition, lactide and styrene, chemicals specific to FFF printing with PLA and ABS based materials,[4] were detected in October 24 samples only in Maker Center. It is noted that the two far from FFF printer locations had higher VOC concentrations than the near printer location for 14 out of the top 15 chemicals for each sampling date, which could be a result of the increased ventilation near FFF printers, or occupants and other activities near these two sampling locations that contributed to VOC emissions.

The passive samples integrated over a week showed similar chemicals as the dynamic samples. **Table 4** lists the chemicals detected from passive samples with higher concentrations in Maker Center than Classroom; 10 out of 24 chemicals were the top 15 detected chemicals from the dynamic samples. The VOCs consistently being detected with higher concentrations in Maker Center included THF, MEK, cyclohexane, 2-propenoic acid, 2-methyl-, 2-hydroxypropyl ester, 1-phenoxypropan-2-ol, lactide, isobornyl methacrylate, methyl methacrylate, xylenes, and ethylbenzene, among which, only 1-phenoxypropan-2-ol and isobornyl methacrylate have not been reported being detected from 3D printing.

TABLE 2: *CONCENTRATIONS (IN UNIT OF MG/M³) OF TOP 15 VOCS DETECTED FROM OCTOBER 24, 2019*

Chemical	Outdoor	Classroom	Printer Near	Printer Far 1	Printer Far 2
Cyclopentasiloxane, decamethyl	3.19	143	53.6	54.2	101
2-Propenoic acid, 2-methyl-, 2-hydroxypropyl ester	0.00	0.00	27.5	24.3	39.0
Xylene (para and/or meta)	3.41	5.00	13.8	17.5	2.85
Formaldehyde	3.85	6.50	6.64	6.62	7.79
iso-Bornyl methacrylate	0.00	0.00	10.5	9.41	15.2
Trimethylbenzene (All Isomers)	1.64	5.86	6.66	7.55	2.47
1-Phenoxypropan-2-ol	0.00	2.95	8.11	7.13	8.31
Toluene (Methylbenzene)	2.30	6.73	3.61	6.79	4.72
Nonyl aldehyde (Nonanal)	0.62	5.47	6.28	6.71	6.44
Acetaldehyde	2.82	4.63	5.59	4.63	5.95
Xylene, ortho	1.07	1.97	6.35	8.23	1.01
Decanal	0.40	6.73	3.75	3.70	5.63
Cyclotetrasiloxane, octamethyl	1.02	4.89	4.56	4.03	3.34
Cyclohexasiloxane, dodecamethyl	0.08	4.90	3.80	3.53	6.96
Benzene, ethyl	1.33	1.62	4.33	5.53	1.18

TABLE 3: *CONCENTRATIONS (IN UNIT OF MG/M³) OF TOP 15 VOCS DETECTED FROM OCTOBER 29, 2019*

Chemical	Outdoor	Classroom	Printer Near	Printer Far 1	Printer Far 2
Cyclopentasiloxane, decamethyl	1.92	127	103	92.8	108
Furan, tetrahydro (THF)	0.00	0.00	14.5	15.9	25.0
2,5-Cyclohexadiene-1,4-dione, 2,5-diphenyl-	0.00	30.8	7.12	2.88	0.00

Chemical	Outdoor	Classroom	Printer Near	Printer Far 1	Printer Far 2
2-Propenoic acid, 2-methyl-, 2-hydroxypropyl ester	0.00	0.00	12.8	11.4	15.9
Cyclohexanone	0.00	0.00	10.3	14.7	17.9
2-Butanone (Methyl ethyl ketone, MEK)	0.00	0.62	11.6	12.8	16.7
Formaldehyde	4.53	9.03	7.59	7.61	9.38
1-Phenoxypropan-2-ol	0.00	4.50	9.09	8.96	12.2
Acetaldehyde	3.98	6.74	6.22	6.17	6.77
2-Butenal	0.00	0.00	1.83	26.3	3.99
Toluene (Methylbenzene)	4.51	4.58	6.16	6.17	6.22
Trimethylbenzene (All Isomers)	3.13	1.98	4.98	6.82	7.59
Cyclohexasiloxane, dodecamethyl	0.04	6.35	4.88	1.77	7.39
Cyclotetrasiloxane, octamethyl	2.95	5.41	3.22	2.59	4.02
Nonyl aldehyde (Nonanal)	0.97	3.43	5.08	5.16	5.17

TABLE 4: *CHEMICALS IN PASSIVE SAMPLES WITH HIGHER CONCENTRATIONS IN MAKER CENTER THAN CLASSROOM*

CAS	Chemical
109-99-9	Furan, tetrahydro (THF)
78-93-3	2-Butanone (Methyl ethyl ketone, MEK)
100-52-7	Benzaldehyde
108-94-1	Cyclohexanone
108-65-6	1-Methoxy-2-propyl acetate
71-43-2	Benzene
98-86-2	Acetophenone (Ethanone, 1-phenyl)
112-40-3	Dodecane

CAS	Chemical
923-26-2	2-Propenoic acid, 2-methyl-, 2-hydroxypropyl ester
770-35-4	1-Phenoxypropan-2-ol
95-96-5	Lactide (1,4-Dioxane-2,5-dione, 3,6-dimethyl-)
7534-94-3	iso-Bornyl methacrylate
6283-14-3	(Bicyclohexyl)-2-amine
53939-27-8	9-Tetradecenal, (Z)-
1000462-98-6	(-)-Isopinocampheol, trimethylacetate
873-49-4	Cyclopropylbenzene
105-05-5	Benzene, 1,4-diethyl
107-74-4	1,7-Octanediol, 3,7-dimethyl
1758-88-9	Benzene, 2-ethyl-1,4-dimethyl
80-62-6	Methyl methacrylate (2-Propenoic acid, 2-methyl-, methyl ester)
616-20-6	Pentane, 3-chloro-
101-83-7	Cyclohexanamine, N-cyclohexyl-
106-42-3	Xylene (para and/or meta)
95-47-6	Xylene, ortho
100-41-4	Benzene, ethyl

Numerous VOCs detected in this field study are irritants, sensitizers, asthmagens, odors, carcinogens, developmental toxins, and reproductive toxins, which can cause adverse health impacts like inflammation, respiratory and neurotoxic symptoms, and cancer. These chemicals of concern are regulated or recommended by governmental agencies and other organizations to maintain good indoor air quality and occupants' health. Crosschecked for the highly detected VOCs with International Agency for Research on Cancer monographs,[8] California Proposition 65,[9] American Conference of Governmental Industrial Hygienists Permissible Exposure Limits,[10] Ausschuss zur gesundheitlichen Bewertung von Bauprodukten Lowest Concentration of Interest values,[11] California Specification 01350,[12] and Office of Environmental Health Hazard Assessment Reference Exposure Levels,[13] chemicals of concern included xylenes, formaldehyde, acetaldehyde, nonanal, decanal, 2-butenal, D5, octamethylcyclotetrasiloxane, dodecamethylcyclohexasiloxane, toluene, ethylbenzene, trimethylbenzene, methyl methacrylate, THF, cyclohexanone, and 2-butanone. Specifically, formaldehyde is a carcinogen, acetaldehyde, ethylbenzene and 2-butenal are potential carcinogens, and toluene is a developmental toxin. All of these VOCs were found emitted from 3D printing, based on 68 chamber tests with various print conditions. In addition, formaldehyde, para- and/or meta-xylene, acetaldehyde, toluene, ethylbenzene, decanal, nonanal, D5 and dodecamethylcyclohexasiloxane were commonly found from 3D printing emissions (detect frequency > 50% for *n* of 68).

Conclusions and Future Work

In this field study, our measurements showed that indoor particulate matter and total volatile organic compound levels in Maker Center with the 3D printers were higher than those found in Classroom. The elevations of ultrafine particle concentrations and 3D printing related VOC species in Maker Center showed the contaminant contribution of 3D printing to the indoor air. Some specific VOCs emissions resulting from 3D printing operations included lactide, styrene, ethylbenzene, formaldehyde, acetaldehyde, nonanal, tetrahydrofuran, cyclohexanone, methyl ethyl ketone, 2-butenal, 2-propenoic acid, 2-methyl-, 2-hydroxypropyl ester, and methyl methacrylate. Over 400 VOCs were measured and many VOCs detected are irritants, sensitizers, asthmagens, odors, carcinogens, developmental toxins, and reproductive toxins, which can cause adverse health impacts like inflammation, respiratory and neurotoxic symptoms, and cancer.

It was also observed that other types of devices and engineering tools in Maker Center can also generate particle and VOC emissions, such as metal processing and laser cutting, in addition to human occupant and activities. Therefore, more studies in school field monitoring are needed to investigate the complete impact of 3D printing on indoor air quality and the role of other activities and ventilation. We continue to conduct field campaigns in various school setups, including university laboratories and classrooms, and primary and secondary school classrooms. In addition to measuring air quality levels, we will also evaluate how engineering control approaches may reduce indoor exposure.

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