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TECHNICAL REPORT

The Impact of 3D Printing on Indoor Air Quality in Educational Settings

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Executive Summary

3D printing is a technology widely used in educational settings, including K-12 schools, that could pose an exposure risk for vulnerable populations, such as children, from unintended emissions. In this field study, Chemical Insights Research Institute (CIRI) monitored the indoor air quality (IAQ), specifically particulate matter (PM) and volatile organic compounds (VOCs), in various locations in K-12 schools and a university to evaluate the impact of material extrusion 3D printers on indoor environments. Studied locations included classrooms in an elementary school and a high school, and a conference room in a university. Studied filament materials included the commonly available acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). Monitoring results showed 3D printing operation could elevate PM in both particle number and mass concentrations, especially near the operating printer. PLA material tended to affect PM number concentration more than ABS, and ABS affected PM mass concentration. It should be noted that background room conditions, such as ventilation, occupancy, cleaning, and other room activities, also affected the indoor PM levels. Similarly, room conditions also contributed to indoor VOC levels. Chemicals associated with cleaning products and personal care products were detected. More importantly, some chemicals known to be emitted from 3D printing were detected with elevated concentrations during printing. These chemicals of concern include known carcinogens, developmental toxins, and irritants, which were consistently detected in all four sampling sites. Among these chemicals of concern, toluene, acetaldehyde, styrene, and naphthalene were likely associated with 3D printing emissions. The study showed that 3D printing increased PM and VOC levels in educational settings during normal use. This exposure to airborne particles and hazardous chemicals could result in short-term irritation or long-term effects for occupants in the classrooms, especially young children, and those with existing respiratory diseases, such as asthma; therefore, raising awareness about appropriate exposure mitigation approaches is needed to reduce the potential for 3D printing related exposures.

1.0 Introduction

3D printers are widely used in educational settings from K-12 schools to universities.[1] They are used for STEAM (science, technology, engineering, art, and math) programs for K-12 schools and for designing and prototyping in universities. 3D printers can be found in classrooms, maker centers, laboratories, and offices on campuses. However, primary and secondary school systems may not be equipped with sufficient ventilation or not have dedicated local exhaust ventilation installed; therefore, an emission source like 3D printing may result in an accumulation of indoor air pollutants and potential health concerns, especially for vulnerable people, such as those with asthma. Previous studies conducted by CIRI have found that material extrusion 3D printing results in ultrafine particle (UFP, smaller than 100 nm) and VOC emissions.[2,3] These pollutants may deteriorate IAQ and, when inhaled, may cause or exacerbate acute or chronic adverse health effects, such as irritation, respiratory and cardiovascular diseases, and cancer.[3,4] It should be noted that only monitoring mass concentration of PM less than or equal to 2.5 microns ($PM_{2.5}$) may not represent the particles in the ultrafine size range, which may underestimate the impacts of 3D printing on IAQ.

CIRI's previous field study, Technical Report R290: Impact of 3D Printing on Indoor Air Quality in a University Maker Center, investigated IAQ in a university maker center and showed that 3D printing could contribute to elevated levels of UFPs and specific VOCs. In the present study, we visited three classrooms in a high school, an elementary school, and a university building where material extrusion 3D printers were used as educational tools for STEAM curricula. We monitored VOC and particle levels in the rooms with printers and evaluated how 3D printing in a normal educational setting might impact IAQ.

2.0 Field Study Methods

2.1 STUDIED MATERIALS AND SAMPLING SITES

Three sites were monitored for airborne particle and VOC levels, which included a high school classroom (High school), an elementary school classroom (Elementary school), and a conference room/classroom in a university (University). Sampling setups at each site are shown in **Figure 1**. In each room, two sampling locations were selected to obtain measurements near and far away from the printer during printing. The 3D printers that were deployed in the monitoring sites have been tested previously in an exposure chamber for emission evaluation and were verified to be low emitting according to the ANSI/CAN/UL 2904 standard.[5] The print materials studied were PLA and ABS from the printer manufacturer. There were two printer models studied, namely P1 and P2; and two types of PLA filaments studied, namely PLA1 and PLA2. The printing conditions followed the manufacturer's instruction for each printer and material; see **Table 1** for details. The print duration was 1.5 to 3 hours depending on the schedule of the visits.

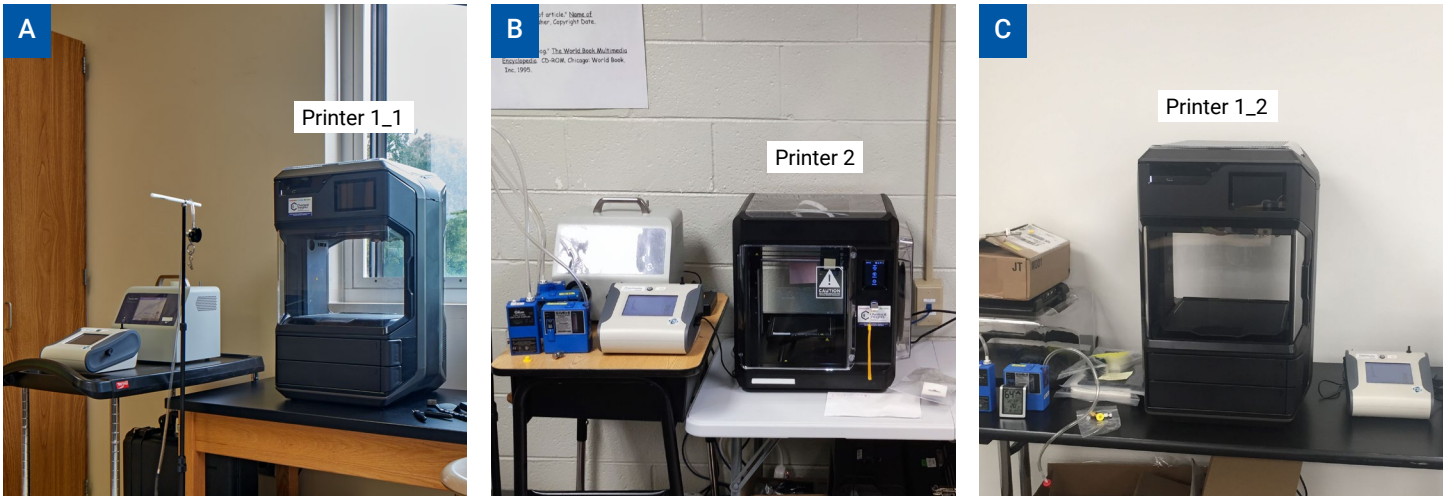

Figure 1: Monitoring sites with 3D printers and sampling instruments for the High school classroom (A), Elementary school classroom (B), and University conference room (C).

Table 1: Printing conditions of studied printers and materials at each site.

Site	Elementary School	High School	University	University
Printer model	P2	P1_1	P1_2	P1_2
Print material	PLA2 black color	ABS black color	ABS black color	PLA1 black color
Print temperature	215 °C	245 °C	245 °C	210 °C

2.2 SAMPLING AND ANALYSIS METHODS

Airborne particle concentration and size distribution for ultrafine nanoscale (10 to 420 nm) particles were measured in real time with a NanoScan Scanning Mobility Particle Sizer (SMPS, TSI 3910) and microscale (0.3 to 10 µm) particles were measured with an Optical Particle Sizer (OPS, TSI 3330). VOC and aldehyde samples were collected using portable pumps connected to Tenax tubes and 2,4-dinitrophenylhydrazine (DNPH) cartridges separately. Furthermore, Tenax tubes were analyzed according to the United States (U.S.) Environmental Protection Agency (EPA) TO-17 method for VOCs using gas chromatography/mass spectrometry, and the DNPH cartridges were analyzed according to the U.S. EPA TO-11A method for low molecular weight aldehydes using high-performance liquid chromatography. See CIRI Technical Brief TB 080: VOC and Aldehyde Analysis Methods Used in Research Studies for a detailed description of these analysis methods. Sampling instruments are shown in **Figure 1**. Particle sampling was conducted throughout the entire monitoring duration, and VOC/aldehyde samples were collected before printing started as a background measurement and during printing. Target active air sample volumes were 18 L for VOCs and 45 L for aldehydes.

3.0 Results

3.1 PARTICLE NUMBER CONCENTRATION

Total particle number concentrations for each site and location are shown in **Figure 2A**. Data are grouped by site (Elementary school, High school, University) and print material (PLA1, PLA2, ABS). Overall particle concentrations were specific to each monitoring site, with Elementary school having the highest concentrations, University with the lowest concentrations, and High school in between the concentrations measured at the other sites. Interestingly, background median concentrations were higher than those during printing at the Elementary school, High school, and University with PLA1, which could be due to the ventilation being operated at low capacity during background sampling when the sites were not open. During printing, the near printer location had higher median concentrations than the far printer location, except for the University site with PLA1. For the University with PLA1 near printer concentrations, there were more data points that were high outliers, which was due to the initial peak of particle concentration after printing started (**Figure 2B**). Previous chamber characterization with PLA1 material also showed an initial peak in number concentration (> 2000 particles/cm^3 in chamber) that dropped quickly during printing. It should be noted that field monitoring may not necessarily follow the pattern observed in a chamber study given different and more complex environmental conditions. In general, 3D printing elevated particle number concentration at near printer locations, while the emissions were diluted and dispersed to the surroundings, far printer locations showed overall lower concentrations than near printer locations.

Laboratory chamber characterization showed PLA2 material had the highest particle emission rate (3.42x108 particles/h) followed by ABS (1.13x108 particles/h), and PLA1 had the lowest emission rate (1.28x104 particles/h). This agrees with the trend of observed particle concentrations, although in different sites. But overall, during printing concentrations were somewhat comparable to the background at each site except outliers; this indicates the particle number concentration was also dependent on the room conditions, ventilation settings, and background levels for that day.

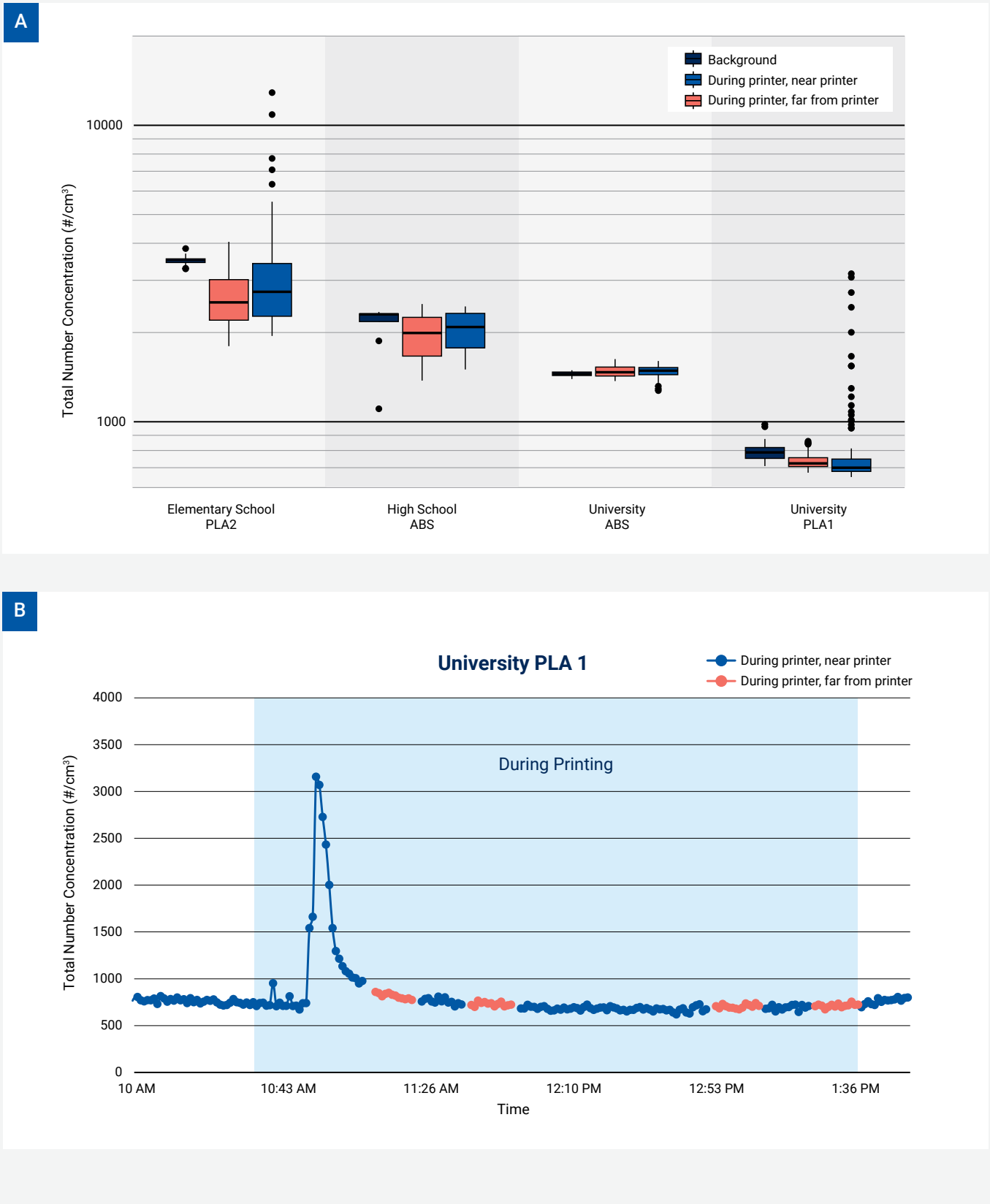

Figure 2: A. Summary box plot of particle number concentrations at different monitoring sites. B. Time series plot of particle number concentration for printing with PLA1 at University site.

3.2 PARTICLE MASS CONCENTRATION

$PM_{2.5}$ concentrations for each site are summarized in **Figure 3**. Overall, $PM_{2.5}$ concentrations monitored were well below the 24-hour $PM_{2.5}$ standard according to the U.S. EPA National Ambient Air Quality Standard (NAAQS, 35 µg/m³). Similar to number concentration trends, medians of $PM_{2.5}$ during printing for the two sites with PLA material were lower than background, which indicates the elevation of particle number concentration near the printer did not increase the mass of particles, while for the two sites with ABS material, the medians were higher during printing for both near and far locations compared to background. This indicates printing with ABS tended to increase $PM_{2.5}$ concentrations with no difference between the locations in the room, which is consistent with the chamber characterization, which showed that ABS material had the highest particle mass emission rate (4.46 µg/h for ABS and smaller than 1 µg/h for PLA). In addition, total inhalable particles (PM_{10}) were typically below 10 µg/m³, while there were a few cases when PM_{10} was above 30 µg/m³. All measured PM_{10} concentrations for the monitoring sites were well below the daily NAAQS (150 µg/m³).

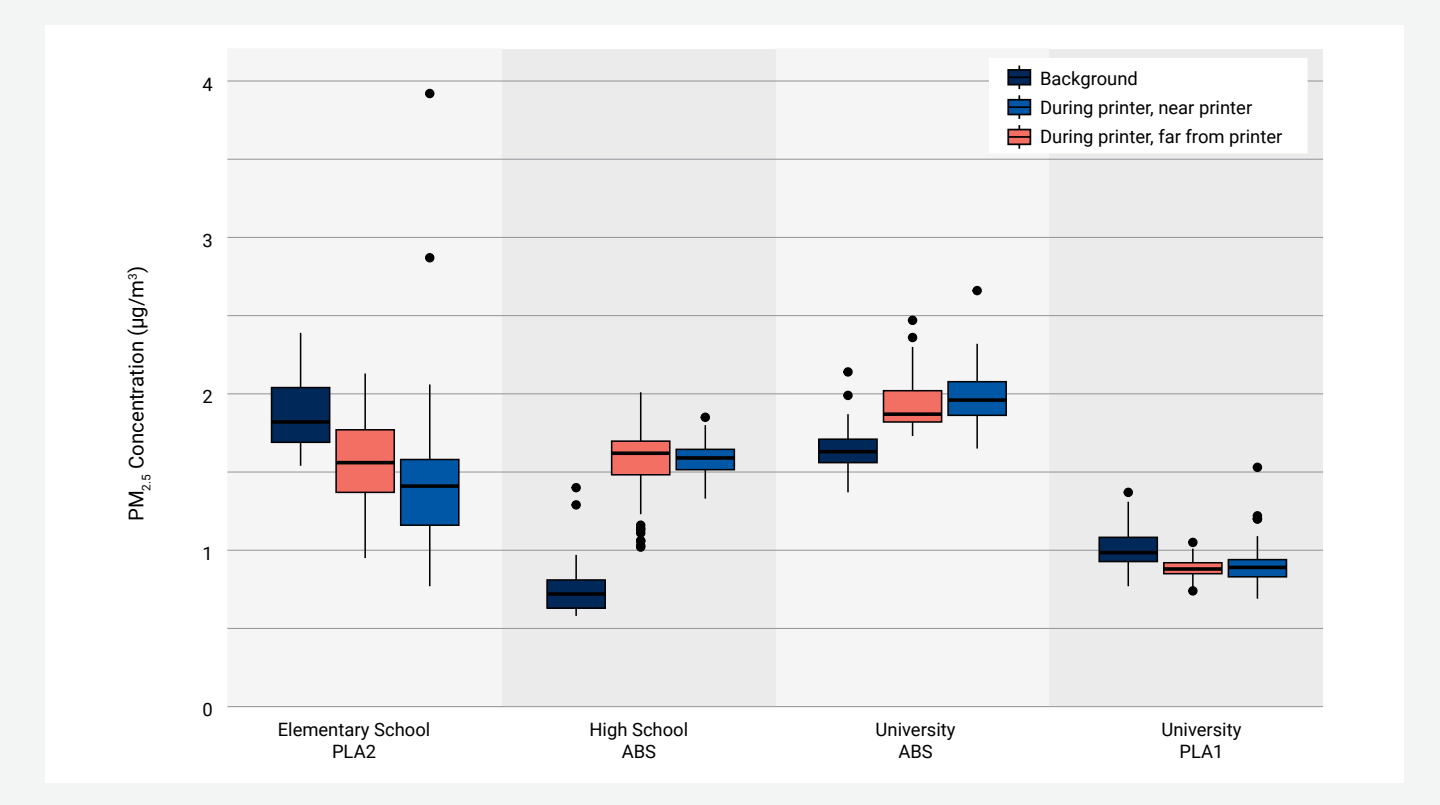

Figure 3: Summary box plot of particle mass concentrations at different monitoring sites.

3.3 TOTAL VOC CONCENTRATION

A comparison of total VOC (TVOC) concentrations at the different sites is shown in **Figure 4**. Overall, TVOC levels were specific to the monitoring site due to differences in emission sources and room conditions. TVOC levels for the High school and Elementary school were much higher than those measured in the University, which is likely associated with the specific setups and cleaning activities in the classrooms. Again, the Elementary school and High school sites showed higher TVOC concentrations during background, which is likely due to the ventilation system not fully operating during school off time when background samples were collected. In addition, High school and Elementary school classrooms had more occupants (approximately 10–20 students and teachers) than University (less than five to at most 10 persons); see the next section for details. For the University site with low TVOC background concentrations, 3D printing tended to elevate TVOC concentrations for both the near and far printer locations. Most of the indoor TVOC concentrations were below 400 µg/m³; however, TVOC in the Elementary school classroom can be higher than the industrial benchmark

level of TVOC concentration for green buildings according to the U.S. Green Building Council Leadership in Energy and Environmental Design (LEED) rating system (500 µg/m^3). Room conditions, such as ventilation, can be important in reducing exposure. The TVOC concentration near the printer that was collected within 1 hour after printing stopped was about 90% of the TVOC compared to during printing (400–500 µg/m^3) in High school, while at University with PLA1, the TVOC level decreased to approximate 30% of that during printing (~ 40 µg/m^3).

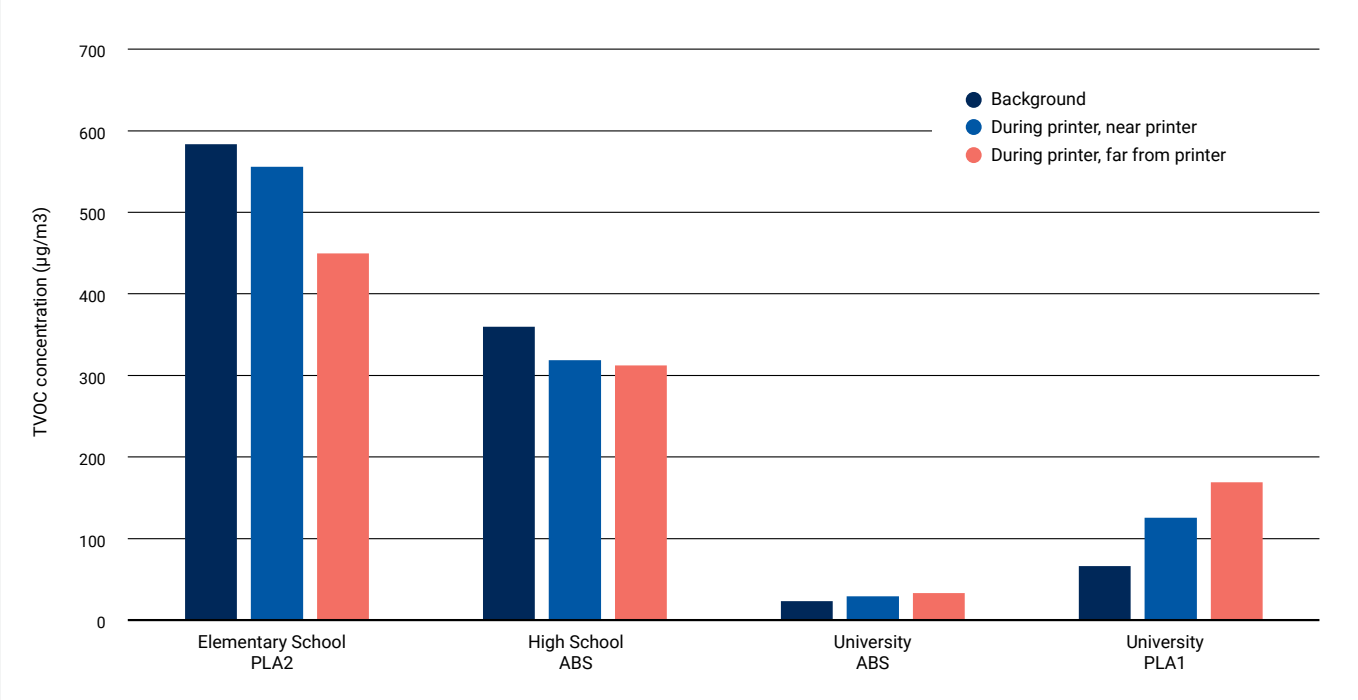

Figure 4: TVOC concentration at different monitoring sites and sampling conditions.

3.4 INDIVIDUAL VOC CONCENTRATION

There were over 200 individual VOCs detected in the field samples and each site had its specific VOC profile. For example, among VOCs with the highest concentrations, 1,3-dioxolane-4-methanol, 2,2-dimethyl- was only found in the Elementary school samples, which is typically associated with cleaning products; ethanol, 2-(2-ethoxyethoxy) was only found in the High school samples, which is typically associated with floor finishing products. The commonly detected VOCs were aldehydes, siloxanes, hydrocarbons, and aromatics. **Table 2** shows the top 10 detected VOCs at each site during printing. The main detected VOCs were those sourcing from cleaning products and personal care products. At the Elementary school site, VOCs with high concentrations, including ethanol, 1,3-dioxolane-4-methanol, 2,2-dimethyl-, propylene glycol, acetic acid, and 2-*tert*-butylcyclohexyl acetate, are associated with cleaning products and air fresheners. Decamethylcyclopentasiloxane (D5) and D-limonene were detected with high concentrations at all sites and are typically found in personal care products and fragrances. The Elementary school and High school sites had higher concentrations likely associated with higher occupancy in the classrooms. Among the VOCs that had an elevated concentration during printing, acetaldehyde and 1-hexanol, 2-ethyl were found to be emitted from PLA material based on chamber characterization; D5 was found to be emitted from PLA1; acetaldehyde, 1-hexanol, 2-ethyl, D5, toluene, and styrene were found to be emitted from the ABS material. Other elevated VOCs could be associated with the occupants and other activities in the room.

Table 2: Top 10 detected VOCs during printing at near printer location with their concentrations (µg/m³).

Elementary School PLA2		High School ABS	
Chemical	**Concentration**	**Chemical**	**Concentration**
Ethanol	299	Ethanol, 2-(2-ethoxyethoxy) (Diethylene glycol monoethyl ether)	105
1,3-Dioxolane-4-methanol, 2,2-dimethyl-	145	Cyclopentasiloxane, decamethyl-	75.9
Cyclopentasiloxane, decamethyl-	41.5	D-Limonene	30.0
2-*tert*-Butylcyclohexyl acetate	29.7	**Ethanol, 2-(hexyloxy)-**	24.5
Hexanoic acid	26.2	**Ethanol, 2-butoxy**	16.4
D-Limonene	20.2	Formaldehyde	11.6
Formaldehyde	17.0	**1-Butanol (N-Butyl alcohol)**	8.6
Acetic acid, hexyl ester	16.7	1,2-Propanediol (Propylene glycol)	7.6
1,2-Propanediol (Propylene glycol)	16.6	Acetaldehyde	6.9
Ethanol, 2-(hexyloxy)-	15.7	**2-Propanol, 1-butoxy**	6.6
University ABS		**University PLA1**	
Chemical	**Concentration**	**Chemical**	**Concentration**
Acetaldehyde	6.4	**Pinene, alpha (2,6,6-Trimethyl-bicyclo[3.1.1]hept-2-ene-)**	12.1
Formaldehyde	5.9	Cyclopentasiloxane, decamethyl-	7.8
Cyclopentasiloxane, decamethyl-	4.0	**Hexanoic acid**	7.7
Toluene (Methylbenzene)	2.9	**Acetaldehyde**	7.5
Propanal	2.4	**1-Hexanol, 2-ethyl**	7.5
1-Hexanol, 2-ethyl	2.4	Formaldehyde	6.4
Benzaldehyde	2.4	D-Limonene	5.7
2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate	2.0	**Pinene, beta (6,6-Dimethyl-2-methylene-bicyclo[3.1.1]heptane-)**	5.3
Nonylaldehyde (Nonanal)	1.9	**Octane, 3-ethyl-2,7-dimethyl**	5.0
Butanal	1.4	**Nonane**	4.9

Note: **Bold** indicates the concentration was elevated during printing compared to background.

There were 83 individual chemicals of concern detected that are regulated by governmental agencies and industrial organizations to maintain good IAQ and occupants' health. These chemicals included irritants, sensitizers, asthmagens, odorants, carcinogens, developmental toxins, and reproductive toxins, and may cause adverse health impacts, such as inflammation, respiratory and neurotoxic symptoms, and cancer. **Table 3** lists hazardous chemicals that were frequently detected (> 50%) and their associated health concerns. 3D printing could contribute to the elevation of some chemicals of concern, since they were also found being emitted based on chamber characterization; such chemicals include acetaldehyde for all three filaments, styrene for PLA2 and ABS, xylenes, toluene, formaldehyde, ethylbenzene, and 2-butoxyethanol for ABS. In addition, formaldehyde is a known carcinogen, and its recommended indoor level is 9 $\mu g/m^3$ according to California Specification 013506; however, formaldehyde concentrations at the Elementary school and High school sites both exceeded this level and reached a maximum concentration over 20 $\mu g/m^3$. Formaldehyde could also be emitted at the sites from other sources, since it is typically found associated with furniture, cleaning products, adhesives, and disinfectants. There were no other individual VOCs that were above the indoor recommended levels. It should be noted that benzene, an International Agency for Research on Cancer (IARC) group 1 human carcinogen, was detected at all sites (**Table 3**). The highest level was 1.06 $\mu g/m^3$, which was close to the California Specification 01350 reference level (1.5 $\mu g/m^3$).[6]

Table 3: Key hazardous chemicals that were frequently detected at monitoring sites with their health concerns.

Chemical	Elementary School PLA2	High School ABS	University ABS	University PLA1	Health Endpoint/ Target Organ System
Benzene	X	X	X	X	*Cancer; developmental, male; **Developmental/ Immune system; Hematologic system
Xylenes (Total)	X	X	**X**	X	**Nervous and respiratory systems; eyes
Toluene (Methylbenzene)	X	**X**	**X**	X	*Developmental/ **Respiratory, nervous systems; eyes reproductive/development
Acetaldehyde	**X**	X	**X**	**X**	*Cancer/ **Eyes; respiratory system (sensory irritation)
Formaldehyde	X	X	**X**	X	*Cancer/ **Eyes (Sensory irritation)
Styrene	**X**	**X**	**X**	X	*Cancer/ **Respiratory system; eyes; reproductive/ development
Ethylbenzene	X	X	**X**	X	*Cancer/ **Alimentary system (liver); kidney; endocrine system; development
Ethanol, 2-butoxy	X	**X**	X		**Eyes and respiratory system
Naphthalene	**X**	**X**		X	*Cancer/ **Respiratory system
7-Methyl-3-methylene-1,6-octadiene (Myrcene)	**X**	X		X	*Cancer
Ethene, 1,1,2,2-tetrachloro (Tetrachloroethylene)	X	**X**	X		*Cancer/ **Nervous system; respiratory system; eyes
Benzophenone (Diphenyl methanone)	**X**	X	X		*Cancer

Note: **Bold** indicates the chemical concentration increased during printing.
*California Office of Environmental Health Hazard Assessment (OEHHA) Proposition 65[7]
**OEHHA Reference Exposure Level (REL) Summary[8]

4.0 Conclusions and Future Work

In this field study, we monitored airborne particle and VOC concentrations in three educational settings and evaluated the impact of 3D printing on IAQ. Our observation shows printing with PLA material tended to elevate particle number concentration, while printing with ABS tended to increase particle mass concentration, with the near printer locations having larger impacts. Site conditions, such as ventilation settings, could contribute largely to the particle levels with and without 3D printing. Similarly, total VOC concentrations were also dependent upon site conditions, with cleaning activities and emissions from occupants contributing largely. 3D printing can be a source of xylenes, toluene, acetaldehyde, formaldehyde, styrene, ethylbenzene, and 2-butoxyethanol in classrooms. Overall, there was no exceedance of particulate levels indoors compared with NAAQS and a few exceedances of TVOC in the elementary school classroom according to LEED criterion. Carcinogenic VOCs such as benzene, formaldehyde, acetaldehyde, ethylbenzene, and styrene had been detected from all three monitoring sites and some of their concentrations increased with the presence of 3D printing. It should be noted that formaldehyde concentrations in the Elementary school and High school sites are higher than the recommended indoor level. Ventilation can be a useful approach to reduce exposure to airborne contaminants. In addition, indoor PM was collected on filters and studied for its toxicity in this study. Human airway epithelial cells that were exposed to the PM showed different extents of cellular injury, inflammation, and oxidative stress, even at relatively low doses. See CIRI Final Report R270: Dosimetric and Toxicological Analysis of 3D Printer Emitted Particles for details. In the future, more field studies are needed to investigate the impact of 3D printing on different indoor environments with several types of 3D printing. Measuring air quality levels and understanding how engineering controls may reduce indoor exposure will also need to be evaluated.

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