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FINAL REPORT

A Research Study of 3D Printing in a University Dental School

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Executive Summary

Vat photopolymerization 3D printing technology has been widely used for dental applications. However, the unintended consequences of using resin and other chemicals on indoor air quality (IAQ) are not well known. This study evaluates the volatile organic compound (VOC) and airborne particulate matter (PM) levels at a large dental school in the southeastern United States, where resin-based 3D printers are routinely used. The sampling locations included two laboratories, which housed either 3D printing or reductive milling devices, respectively, and an interior hallway. The 3D printing laboratory had the highest levels of VOCs detected, followed by the hallway and the milling room. Among the most abundantly detected VOCs, two (N-acrylylmorpholine and 2-methyl, 2-hydroxyethyl ester 2-propenoic acid) were detected only in the 3D printing laboratory, likely associated with the resin used. Other significant VOCs likely associated with resin 3D printing and post-processing activities included 2-butoxyethanol, decamethylcyclopentasiloxane, methyl methacrylate, 2-(2-ethoxyethoxy) ethanol, formaldehyde, and toluene. Exposure to these VOCs may pose health concerns to people, as some are carcinogenic, irritating, or sensitizing. Of the VOCs known to be associated with 3D printing operations, only formaldehyde was found to exceed any indoor air quality reference criteria, which was the chronic reference exposure level developed by the California Office of Environmental Health Hazard Assessment. The milling laboratory had the highest mass of PM, corresponding with the observation of larger particle sizes present in this location compared to the 3D printing laboratory and the hallway. All three locations showed fine, nanometer-sized (nm) particles dominating the number size distributions. The hallway had the highest total number concentration, which is about three times that in the laboratories. Overall, resin-based 3D printers, including associated post-processing activities, were observed to primarily emit VOCs inside the studied educational indoor environment. This could result in acute or chronic exposure to hazardous chemicals. More studies are needed to evaluate the impacts of resin-based 3D printing on indoor air quality and develop solutions for reducing exposure and health risks.

1.0 Introduction

3D printers have been widely used in schools, offices, and homes. However, depending on the type of 3D printing technology, the use of 3D printers can generate particulate matter (PM) and volatile organic compounds (VOCs), which may pose health concerns to the users. Chemical Insights Research Institute (CIRI) of UL Research Institutes has been characterizing the emissions from 3D printing of diverse types and conditions. CIRI has found that material extrusion 3D printing generates elevated levels of ultrafine particles and various hazardous VOCs, but data for vat photopolymerization 3D printing is limited for assessment.

Vat photopolymerization technology uses photopolymer resin that can be cured selectively by light-activated polymerization. This type of 3D printing can create finely detailed parts with a smooth surface finish, making it widely used for dental and medical applications. CIRI's preliminary data show stereolithography (SLA) 3D printing, a type of vat photopolymerization, emits primarily VOCs, including sensitizers, carcinogens, and irritants.

CIRI recently partnered with the Campus, Safety, Health, and Environmental Management Association (CSHEMA) to produce the guidance document [UL200B Safe Use of 3D Printing for Institutions of Higher Education](). The publication of this document has raised awareness of 3D printing safety on college campuses and helped identify gaps in knowledge and best practices. Since vat photopolymerization is routinely used in dental schools, more data is needed on emissions and health concerns in these settings.

Figure 1: Breathing Zone Air Sample Collection for VOCs and Aldehydes.

This report covers CIRI's recent collaboration with a large dental school in the southeastern United States for a research study on potential airborne hazards associated with new technologies and methods being used in modern dentistry and dental education. Of particular interest was the impact of vat photopolymerization 3D printing processes on air quality. This study evaluated indoor air quality by conducting air measurements in three locations, including a laboratory that housed 3D vat photopolymerization printing processes, a laboratory that housed computer-aided milling equipment, and a hallway as a non-activity reference. Air measurements were made for VOCs, formaldehyde, other aldehydes, and airborne particulates.

2.0 Field Study Methods

2.1 SAMPLING LOCATIONS

Air samples were collected in three locations within the dental school. Testing location 1 was the 3D printing laboratory, which contained multiple resin-based 3D printing systems, solvent (ethanol) baths, and curing machines (**Figure 2**). Testing location 2 was the milling laboratory, which contained various reductive milling devices (**Figure 3**: These devices carve out 3D shapes based on high-resolution computer models and images). Testing location 3 was the third-floor hallway of the dental school building. This hallway was in the same building as the 3D printing laboratory. The milling laboratory, however, was in a contiguous but separate building.

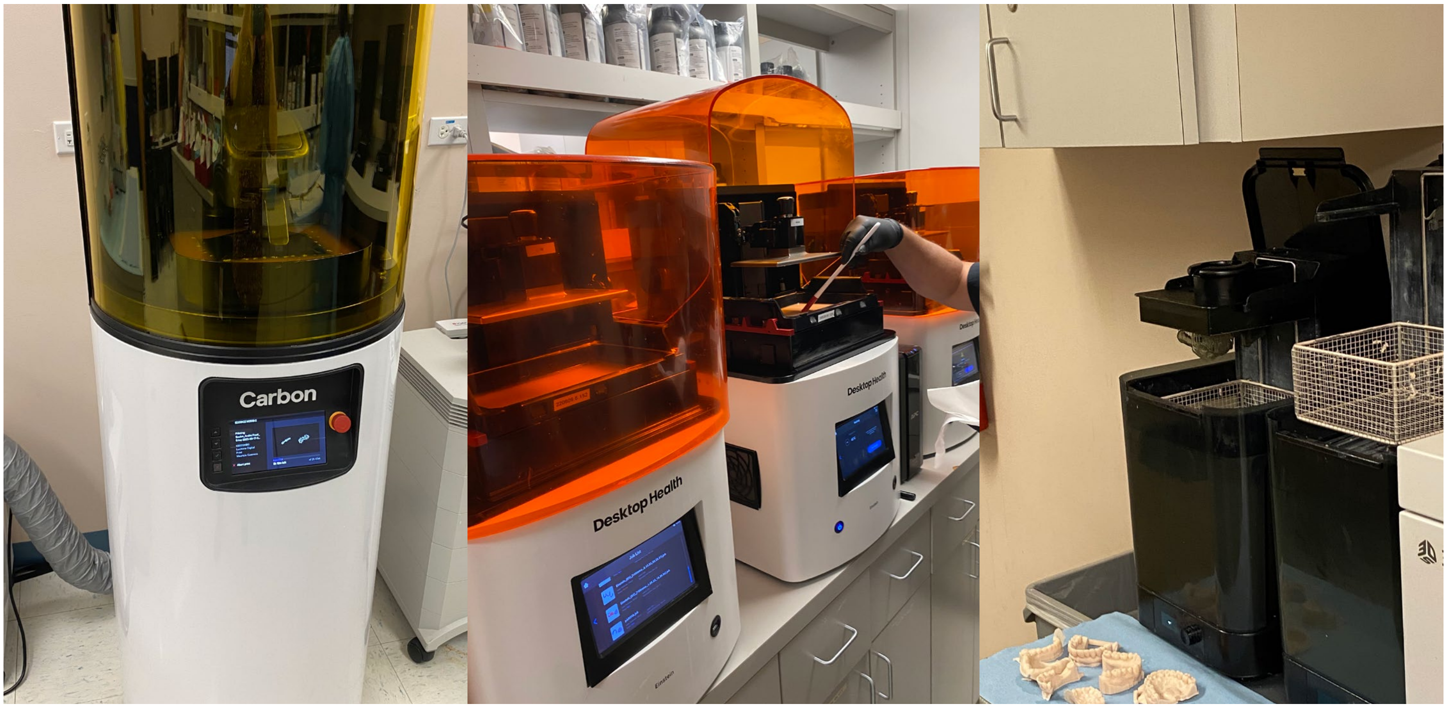

Figure 2: 3D Printing Laboratory. Left and Middle: 3D Resin Printers; Right: Solvent Curing Baths.

Figure 3: Milling Machines in Use in the Milling Laboratory.

2.2 SAMPLING AND ANALYSIS METHODS

Airborne measurements were taken in the three locations using active air sampling strategies for VOCs, formaldehyde, and other low-molecular-weight carbonyl compounds. Active air sampling was taken for one hour in the two laboratories and two hours in the hallway. The sample flow rate was 0.2 L/min for VOCs and 0.5 L/min for aldehydes, controlled via calibrated personal sampling pumps.

VOCs were collected using Tenax® TA sorbent tubes, which were thermally desorbed and analyzed by thermal desorption-gas chromatography/mass spectrometry (TD-GC/MS) according to ASTM D6196 and US EPA Methods TO-17 and TO-1. This analysis protocol separates and detects VOCs with boiling points ranging approximately 35–250 °C or C6–C16. A laboratory-specific spectral database of approximately 700 VOCs is used to identify individual VOCs collected by the sampling media. The VOCs in this database have been previously found in indoor air and product emissions studies and validated by the laboratory for analysis using laboratory-specific systems. By matching spectral characteristics and retention times based on the laboratory method, the identification is accurate with little uncertainty, down to a quantitation level of approximately 0.5 μg/m^3 for most common VOCs. A general mass spectral library, available from the National Institute of Standards and Technology (NIST), which includes the characteristics of more than 75,000 compounds, is used for those VOCs detected but not identified by the laboratory spectral database. Mass spectral characteristics and compounds are identified if they show an 80% match. All VOCs are quantified from multi-point calibration curves prepared using authentic standards if available; otherwise, they were calibrated relative to toluene. Authentic standard calibrations are available for 73 specific VOCs, the most commonly measured VOCs listed by various IAQ or regulatory programs. The measurement is reported as a toluene equivalent for compounds that do not have an authentic standard. Calculations for total volatile organic compound (TVOC) levels are made by taking the total GC/MS scan response between C6 and C16 and converting it to a concentration based on a toluene equivalent.

Aldehydes were collected onto DNPH (2,4-dinitrophenylhydrazine) sorbent cartridges, which were solvent desorbed and analyzed by high-performance liquid chromatography (HPLC) according to ASTM D5197 and US EPA Method TO-11A. Specific target species are quantified using a multi-point internal calibration method prepared from hydrazone derivatives of the pure compounds. Target aldehydes include formaldehyde, acetaldehyde, 2-propenal, acrolein, propanal, 2-butenal, butanal, benzaldehyde, 3-methylbutanal, pentanal, 2-methylbenzaldehyde, 3- and 4-methylbenzaldehyde, hexanal, and 2,5-dimethylbenzaldehyde. Aldehydes are also reported at a quantitation level of approximately 0.5 μg/m^3.

Particulates were measured using direct reading instruments to evaluate airborne particulate concentrations and size distributions. A NanoScan scanning mobility particle sizer (SMPS, TSI) and an optical particle sizer (OPS, TSI) were used to measure particles from 10 nm to 10 μm. Particle monitoring instruments ran continuously during the sampling period, with a sample interval of one minute.

All measurements were done at table height or elevated to represent exposure within an average person's typical breathing zone (i.e., about head level).

The data presented here are research-based and presented for informational purposes. Occupational compliance and/or health risk assessments were not conducted, and these data should not be used for those purposes.

3.0 Results

3.1 AEROSOL MONITORING

Airborne particulate matter was evaluated in real time using TSI NanoScan and optical particle sizing instruments. Combining the data streams from these two instruments allows for the generation of size- and time-resolved air monitoring data. Particle data analyzed by considering the total particle number (N) is shown in Figure 4. Considering particle number as a readout, the hallway had the highest number of particles detected, and they are predominantly smaller than 200 nm, with a peak size of approximately 30 nm. Similarly, nm-sized particles dominated the average particle size distributions observed in the two laboratories (Figure 4). It is noted that ultrafine particles (smaller than 100 nm in size) would pose higher health concerns due to the specific properties associated with the small sizes. The total particle concentrations, integrating all measured sizes, are summarized in Table 1. The total particle number concentrations in the 3D printing laboratory were generally lower than those measured in the hallway. Our previous study also showed that resin 3D printing emits limited particles.[1] The lower observed particle number concentrations in the two laboratories could also be due to higher ventilation capacities in laboratories.

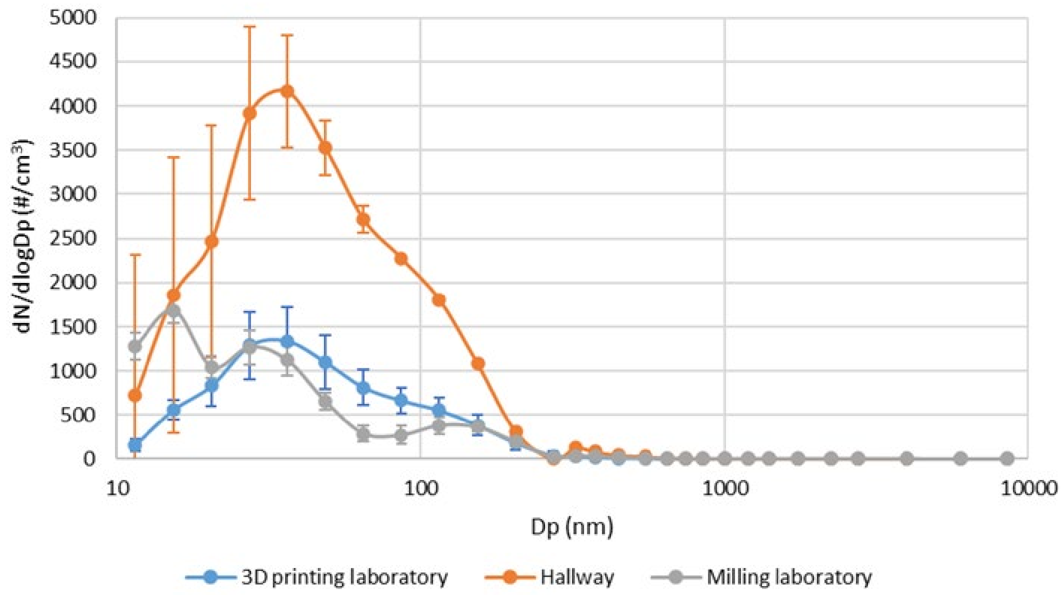

Figure 4: Particle Number Size Distribution in Three Sampling Locations.

Table 1: Summary of Total Particle Concentrations (Mean ± Standard Deviation) in Different Sampling Locations

Location	Particle number (N, #/cm^3)	Particle mass (M, μg/m^3)
3D printing laboratory	(1.00 ± 0.20) × 10^3	1.94 ± 0.91
Hallway	(3.13 ± 1.03) × 10^3	24.3 ± 21.9
Milling laboratory	(1.08 ± 0.08) × 10^3	62.1 ± 7.9

It is also important to consider that small particles do not have significant mass compared to larger particles, and the total inhaled mass of an airborne agent is a common way to conceptualize or calculate a "dose." Figure 5 shows the size distributions with particle mass (M) as the primary readout. It is observed that the particle sizes corresponding to high relative masses were between 1 and 10 microns in diameter. The milling laboratory showed the highest concentrations in this size range. The total particle mass concentrations are shown in Table 1. The largest particles are also the most massive. Therefore, the milling laboratory had the highest particle mass levels, followed by the hallway. It is important to know that monitoring for $PM_{2.5}$ (PM smaller than 2.5 μm in size) and ultrafine particles, as frequently done in indoor air studies, would underestimate the mass-based exposure potential by excluding larger particles from measurement. In this study, the average $PM_{2.5}$ level in the milling laboratory was 3.4 ± 0.6 μg/m^3, which is comparable to that in the hallway (4.2 ± 1.6 μg/m^3), while the average PM_{10} level in the milling laboratory is over two times higher than that in the hallway (Table 1).

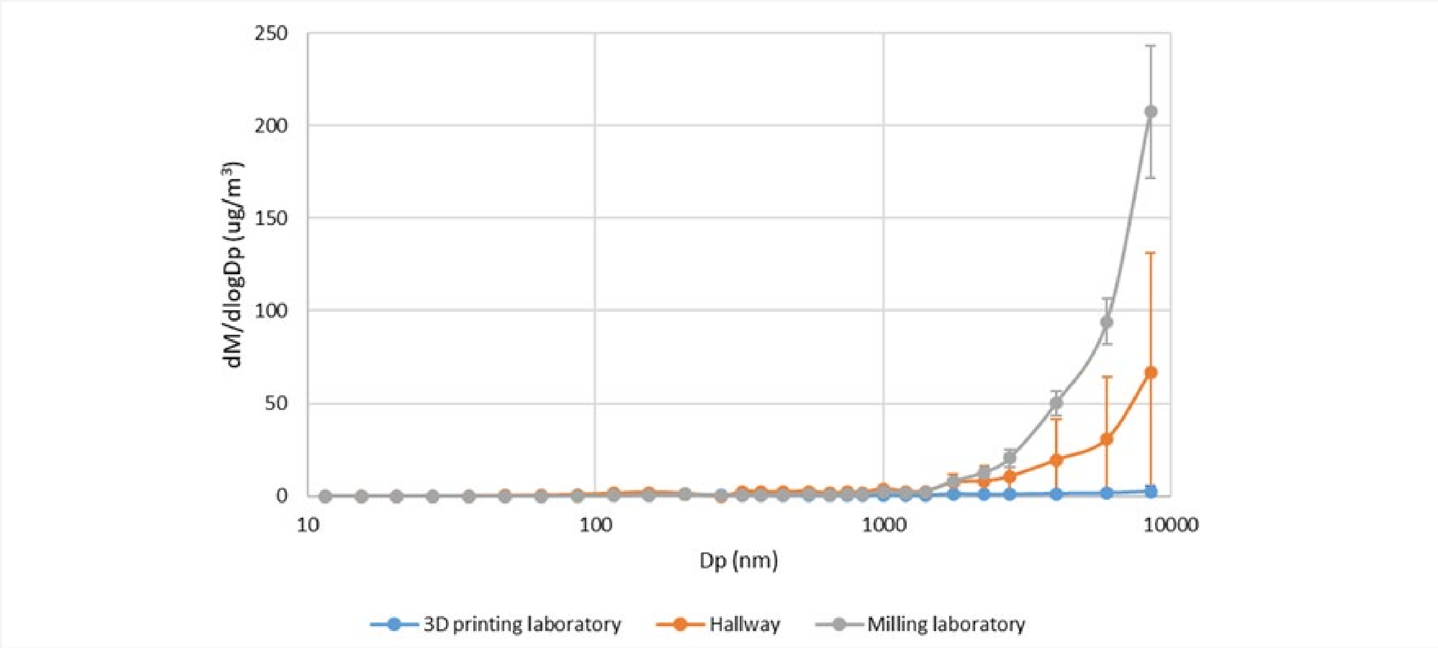

Figure 5: Particle Mass Size Distribution in the Sampling Locations.

3.2 VOC ASSESSMENT

The TVOC levels measured in all locations are shown in Figure 6. The higher loads of VOCs were found in the 3D printing laboratory and hallway. In general, levels of TVOC found in the three locations were within the generally acceptable range of 300–500 μg/m^3 for IAQ. However, numerous VOCs were found with low levels, especially in the 3D printing laboratory and hallway, and were likely associated with the printing processes. These included a large number of acrylates, siloxanes, alcohols, glycol ethers, aldehydes, and others.

The number of VOCs and specific VOCs found were similar in the 3D printing laboratory and the hallway. Primary VOCs detected are shown in Table 2, with a full listing of all VOCs found in Appendix A. Overall, about 150 different VOCs were measured.

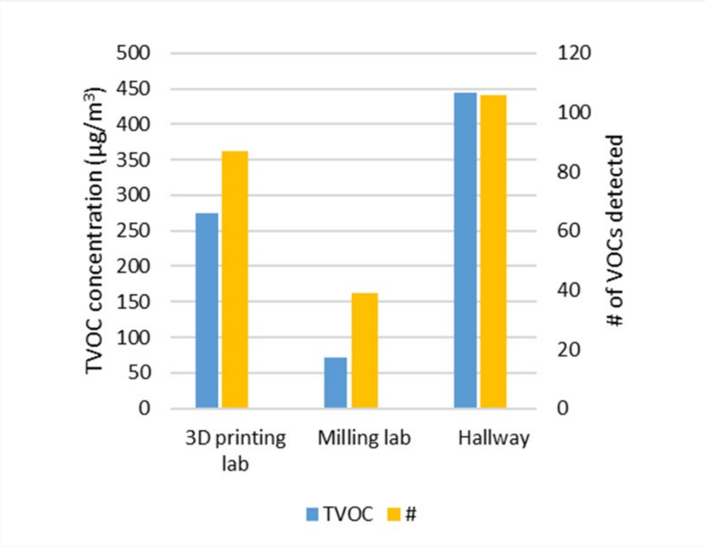

Figure 6: TVOC Levels and Number of VOCs Detected for Each Sample Location.

The most abundant VOCs measured in the 3D printing laboratory are likely attributable to the resin-based 3D printing processes based on the formula of the resin. This includes acryloylmorpholine and numerous acrylates. The substituted ethanolic compounds may be associated with post-processing operations. Since the specific VOCs found in these two locations are similar, there also appears to be entrainment of these printing-related VOCs in the hallway. VOCs, in general, were lower and different in the milling laboratory, but that process was in a different building.

Of the primary VOCs associated with the 3D printing process (Table 2: 3D printing lab), ethanol, 2-butoxy, cyclopentasiloxane, decamethyl, methyl methacrylate, ethanol, 2-(2-ethoxyethoxy), formaldehyde, toluene, and heptane were found to be specific chemicals of concern that fall on various health hazard criteria lists for general indoor air exposure.[2–7] Specifically, formaldehyde is carcinogenic; toluene is a developmental toxin; and methyl methacrylate is a sensitizer.[1,2,7] Among these chemicals of concern, ethanol, 2-(2-ethoxyethoxy), likely associated with the wash process, is not currently listed in the ANSI/CAN/UL 2904 standard.[8] There are no exceedances compared to published and commonly used VOC reference concentration limits except formaldehyde in the 3D printing laboratory and hallway (9 µg/m³).[4,8]

Table 2: Top 10 Detected VOCs in Each Sampling Location (Concentrations in µg/m³)

CAS	Chemical	3D printing lab	Milling lab	Hallway
5117-12-4	N-Acryloylmorpholine	102		
111-76-2	Ethanol, 2-butoxy	82.7	8.9	72.1
541-02-6	Cyclopentasiloxane, decamethyl	54.5	21.4	58.7
80-62-6	Methyl methacrylate (2-Propenoic acid, 2-methyl-, methyl ester)	42.6	2.7	39.0
111-90-0	Ethanol, 2-(2-ethoxyethoxy) (Diethylene glycol monoethyl ether)	38.9	5.3	25.5
50-00-0	Formaldehyde	23.5	7.9	24.6
108-88-3	Toluene (Methylbenzene)	21.1	8.1	18.5
868-77-9	2-Propenoic acid, 2-methyl-, 2-hydroxyethyl ester	19.8		
5989-27-5	D-Limonene	18.9	*1.4*	23.3
142-82-5	Heptane	12.1		40.4
75-07-0	Acetaldehyde	*1.8*	8.5	*1.6*
75-09-2	Methylene chloride (Dichloromethane)	*2.5*	3.0	
104-76-7	1-Hexanol, 2-ethyl	*5.6*	2.4	*4.4*
124-13-0	Octanal		2.1	*9.7*
108-87-2	Cyclohexane, methyl	*8.2*		15.8
589-34-4	Hexane, 3-methyl	*4.6*		11.2

* A blank cell indicates the VOC was not detected in that specific location; *italic* value indicates the VOC was detected but was not in the top 10 list for that specific location.

4.0 Conclusions

The resin-based 3D printing processes appear to add numerous VOCs to the indoor air, including ones that are likely irritants and odorants. Our current target analyte list for GC/MS analysis does not include ethanol. Since ethanol is the solvent used for the curing step of 3D-printed dental devices, it is expected to be present and could be measured with additional testing using an appropriate method. All detected VOCs were cross-referenced with common IAQ and occupational health guidelines. Formaldehyde exceeded the California EPA guidelines in the 3D printing laboratory and hallway. For most VOCs measured, there were no recommended limits.

This is a preliminary field study to identify specific airborne contaminants that could be emitted from resin-based 3D printing systems. Numerous VOCs were detected, which indicated that the resin-based printing systems could add process-specific VOCs to indoor air. Since many are odorants and irritants, source control with proper placement of printing locations, ventilation, and exhaust systems is likely warranted.

The resin-based 3D printers in this study tended to release a limited number of particles in both number and mass concentrations. However, the dominant particle sizes in the 3D printing laboratory were small and within 200 nm in diameter, which may pose health concerns when inhaled.

5.0 Future Direction

This type of information would be valuable for occupational health professionals who oversee operations at dental schools, where the rapidly changing technology landscape may introduce new and unexpected impacts on IAQ. A more detailed future study emphasizing chemical-specific methods and building ventilation could add additional insights.

6.0 References

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3. ASHRAE. ASHRAE/USGBC/IESNA Standard 189.1, Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings, 2020.
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7. OEHHA. *The Proposition 65 List*. OEHHA. https://oehha.ca.gov/proposition-65/proposition-65-list (accessed 2023-04-03).
8. ANSI. ANSI/CAN/UL 2904:2023 Standard Method for Testing and Assessing Particle and Chemical Emissions from 3D Printers, 2023.

7.0 Appendix

Appendix. Complete VOC Concentration Results (µg/m³)

CAS	Chemical	3D printing lab	Milling lab	Hallway
75-07-0	Acetaldehyde	1.8	8.5	1.6
141-78-6	Acetate, ethyl	2.8	1.1	1.7
140-11-4	Acetic acid, phenylmethyl ester (Benzyl acetate)			0.9
98-86-2	Acetophenone (Ethanone, 1-phenyl)	8.1	0.6	1.5
101-86-0	a-Hexylcinnamaldehyde [Octanal, 2-(phenylmethylene)]			0.8
142-19-8	Allyl heptanoate			0.9
79-70-9	a-Methylionone			4.0
100-52-7	Benzaldehyde	4.8	1.0	2.5
101-84-8	Benzene, 1,1'-oxybis- (Diphenyl ether)	1.2		1.2
611-14-3	Benzene, 1-ethyl-2-methyl (2-Ethyltoluene)	0.7		
100-41-4	Benzene, ethyl	1.6		0.9
617-94-7	Benzenemethanol, a,a-dimethyl-	3.1		
119-36-8	Benzoic acid, 2-hydroxy-, methyl ester			2.6
119-61-9	Benzophenone (Diphenyl methanone)	1.2		
123-72-8	Butanal		0.8	
112-73-2	Butane, 1,1'-[oxybis(2,1-ethanediyloxy)]bis- (Butyl diglyme)			1.5
1000357-86-8	Carbonic acid, 2-methoxyethyl phenyl ester		1.1	
107-50-6	Cycloheptasiloxane, tetradecamethyl-		0.7	3.4
108-87-2	Cyclohexane, methyl	8.2		15.8
108-94-1	Cyclohexanone	1.9		1.3
14073-97-3	Cyclohexanone, 5-methyl-2-(1-methylethyl)-, (2S-trans)-		0.6	4.2
540-97-6	Cyclohexasiloxane, dodecamethyl		1.6	4.1
1222-05-5	Cyclopenta[g]-2-benzopyran, 1,3,4,6,7,8-hexahydro-4,6,6,7,8,8-hexamethyl-			0.6
53366-38-4	Cyclopentane, (2-methylbutyl)			0.6
2452-99-5	Cyclopentane, 1,2-dimethyl	1.3		2.2

Appendix. Complete VOC Concentration Results (µg/m³)

CAS	Chemical	3D printing lab	Milling lab	Hallway
2532-58-3	Cyclopentane, 1,3-dimethyl, cis	1.2		2.8
1759-58-6	Cyclopentane, 1,3-dimethyl, trans	1.1		2.7
1640-89-7	Cyclopentane, ethyl	1.1		3.0
541-02-6	Cyclopentasiloxane, decamethyl	54.5	21.4	58.7
556-67-2	Cyclotetrasiloxane, octamethyl	4.4	1.0	2.6
541-05-9	Cyclotrisiloxane, hexamethyl	1.5		1.1
112-31-2	Decanal	3.6	1.1	2.4
1000406-38-3	Decyl octyl ether	2.3		3.5
5989-27-5	D-Limonene	18.9	1.4	23.3
112-54-9	Dodecanal			1.5
112-40-3	Dodecane	2.7		
31295-56-4	Dodecane, 2,6,11-trimethyl			2.6
61141-72-8	Dodecane, 4,6-dimethyl			2.1
64-17-5	Ethanol	0.6		
112-34-5	Ethanol, 2-(2-butoxyethoxy)	1.3		
111-90-0	Ethanol, 2-(2-ethoxyethoxy) (Diethylene glycol monoethyl ether)	38.9	5.3	25.5
111-76-2	Ethanol, 2-butoxy	82.7	8.9	72.1
110-80-5	Ethanol, 2-ethoxy	1.2		1.4
122-99-6	Ethanol, 2-phenoxy	1.7		
470-82-6	Eucalyptol	3.2	1.8	3.3
50-00-0	Formaldehyde	23.5	7.9	24.6
629-78-7	Heptadecane			1.2
142-82-5	Heptane	12.1		40.4
7225-67-4	Heptane, 2,2,3,3,5,6,6-heptamethyl	2.6		
2216-30-0	Heptane, 2,5-dimethyl			2.5
17302-01-1	Heptane, 3-ethyl-3-methyl			0.5
541-01-5	Heptasiloxane, hexadecamethyl-			2.4
544-76-3	Hexadecane (Cetane)			2.1
66-25-1	Hexanal		1.5	1.9

Appendix. Complete VOC Concentration Results (µg/m³)

CAS	Chemical	3D printing lab	Milling lab	Hallway
110-54-3	Hexane	5.6		5.8
591-76-4	Hexane, 2-methyl	3.0		8.0
589-34-4	Hexane, 3-methyl	4.6		11.2
142-62-1	Hexanoic acid			0.6
1000406-82-2	Hexanoic acid, 3,5,5-trimethyl-, 2-ethylhexyl ester			1.1
107-52-8	Hexasiloxane, tetradecamethyl	1.9		
1000132-07-5	Indan-1,3-diol monopropionate			1.6
2756-56-1	Isobornyl propionate	5.2		
689-12-3	Isopropyl acrylate	0.6		
80-54-6	Lilial			0.7
115-95-7	Linalyl acetate (1,6-Octadien-3-ol, 3,7-dimethyl-, acetate)	1.2		1.0
1490-04-6	Menthol	3.2	1.1	4.0
80-62-6	Methyl methacrylate (2-Propenoic acid, 2-methyl-, methyl ester)	42.6	2.7	39.0
75-09-2	Methylene chloride (Dichloromethane)	2.5	3.0	
5117-12-4	N-Acryloylmorpholine	102		
91-20-3	Naphthalene	0.7		0.6
93-04-9	Naphthalene, 2-methoxy-		0.6	
4390-04-9	Nonane, 2,2,4,4,6,8,8-heptamethyl	2.6		1.9
124-19-6	Nonyl aldehyde (Nonanal)	8.6	2.1	5.5
124-13-0	Octanal		2.1	9.7
1071-31-4	Octane, 2,2,7,7-tetramethyl	1.2		
15869-93-9	Octane, 3,5-dimethyl			1.6
15869-95-1	Octane, 4,4-dimethyl			1.8
2216-34-4	Octane, 4-methyl	0.5		
629-62-9	Pentadecane	4.0		3.7
1921-70-6	Pentadecane, 2,6,10,14-tetramethyl			2.2
109-66-0	Pentane		2.1	
565-59-3	Pentane, 2,3-dimethyl	0.9		0.8
107-83-5	Pentane, 2-methyl	3.5		6.5

Appendix. Complete VOC Concentration Results (µg/m³)

CAS	Chemical	3D printing lab	Milling lab	Hallway
96-14-0	Pentane, 3-methyl	0.9		2.1
96-76-4	Phenol, 2,4-bis(1,1-dimethylethyl)-	5.4		
80-56-8	Pinene, alpha (2,6,6-Trimethyl-bicyclo[3.1.1] hept-2-ene)	0.9	0.6	0.8
123-38-6	Propanal	10.6		9.2
10411-92-4	p-tert-Butyl cyclohexyl-acetate cis			2.0
629-59-4	Tetradecane	3.9	0.7	3.5
110-27-0	Tetradecanoic acid, 1-methylethyl ester (Isopropyl Myristate)	0.9		0.6
17831-71-9	Tetraethylene glycol diacrylate	3.8		
108-88-3	Toluene (Methylbenzene)	21.1	8.1	18.5
107-51-7	Trisiloxane, octamethyl			1.3
6846-50-0	TXIB (2,2,4-Trimethyl-1,3-pentanediol diisobutyrate)	3.0	0.8	4.3
17312-82-2	Undecane, 4,6-dimethyl			0.9
	Unidentified	6.3		
1330-20-7	Xylenes (Total)	6.6	0.6	3.0
19903-73-2	(3R,3aS,6S,7R)-3,6,8,8-Tetramethyloctahydro-1H-3a,7-methanoazulen-6-ol			1.2
2244-16-8	(S)-(+)-Carvone	1.4		1.4
10595-06-9	.beta.-Phenoxyethyl methacrylate	9.0		
1000367-08-6	1-(1-Methoxypropan-2-yloxy)propan-2-yl acetate	1.8		6.1
57-55-6	1,2-Propanediol (Propylene glycol)		0.6	
107-88-0	1,3-Butanediol		1.1	
99-85-4	1,4-Cyclohexadiene, 1-methyl-4-(1-methylethyl)-	2.3		1.1
13048-33-4	1,6-Hexanediol diacrylate	4.8		
71-36-3	1-Butanol (N-Butyl alcohol)	4.1	0.9	2.2
112-30-1	1-Decanol (N-Decyl alcohol)			0.7
10042-59-8	1-Heptanol, 2-propyl			1.7
104-76-7	1-Hexanol, 2-ethyl	5.6	2.4	4.4
61142-60-7	1H-Indene, 2,3,3a,4,7,7a-hexahydro-2,2,4,4,7,7-hexamethyl-			0.8

Appendix. Complete VOC Concentration Results (µg/m^3)

CAS	Chemical	3D printing lab	Milling lab	Hallway
54832-81-4	1H-Indene, 2,3,3a,4,7,7a-hexahydro-2,2,4,4,7,7-hexamethyl-, trans-			1.7
111-87-5	1-Octanol			0.6
127-43-5	1-Penten-3-one, 1-(2,6,6-trimethyl-1-cyclohexen-1-yl)-	1.5		
106-62-7	1-Propanol, 2-(2-hydroxypropoxy)	3.6	0.6	3.5
5171-85-7	2,2,4,4,5,5,7,7-Octamethyloctane			0.8
25265-77-4	2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate	4.5	0.7	5.2
868-91-7	2,2,5,5-Tetramethyl-3-hexanone			1.3
2460-77-7	2,5-di-tert-Butyl-1,4-benzoquinone			3.4
108-10-1	2-Pentanone, 4-methyl (Methyl isobutyl ketone, MIBK)		1.1	0.8
29911-28-2	2-Propanol, 1-(2-butoxy-1-methylethoxy)- (Dipropylene glycol monobutyl ether)	7.8	1.5	9.5
20324-32-7	2-Propanol, 1-(2-methoxy-1-methylethoxy)			1.0
5131-66-8	2-Propanol, 1-butoxy	1.0		0.9
1569-01-3	2-Propanol, 1-propoxy	0.5		
49582-42-5	2-Propenal, 3-(1-aziridinyl)-3-(dimethylamino)-	1.7		
103-11-7	2-Propenoic acid, 2-ethylhexyl ester (2-Ethylhexyl acrylate)	1.0		1.1
818-61-1	2-Propenoic acid, 2-hydroxyethyl ester	4.7		
79-41-4	2-Propenoic acid, 2-methyl	1.7		
97-90-5	2-Propenoic acid, 2-methyl-, 1,2-ethanediyl ester	5.4		
868-77-9	2-Propenoic acid, 2-methyl-, 2-hydroxyethyl ester	19.8		
923-26-2	2-Propenoic acid, 2-methyl-, 2-hydroxypropyl ester	2.1		
7779-31-9	2-Propenoic acid, 2-methyl-, 3,3,5-trimethylcyclohexyl ester	7.3		
101-43-9	2-Propenoic acid, 2-methyl-, cyclohexyl ester	2.9		
88-41-5	2-tert-Butylcyclohexyl acetate		0.6	7.0
1000189-13-7	3,7,7-Trimethyl-1-(3-oxo-but-1-enyl)-2-oxa-bicyclo[3.2.0]hept-3-en-6-one	3.2		

Appendix. Complete VOC Concentration Results (μg/m³)

CAS	Chemical	3D printing lab	Milling lab	Hallway
78-70-6	3,7-Dimethyl-1,6-octadien-3-ol (Linalool)			1.8
72934-06-6	3,7-Dimethyloct-6-en-1-yl decanoate			1.3
98-55-5	3-Cyclohexene-1-methanol, a,a,4-trimethyl			1.4
80-26-2	3-Cyclohexene-1-methanol, a,a,4-trimethyl-, acetate			1.9
123-48-8	3-Heptene, 2,2,4,6,6-pentamethyl-	0.7		
1000432-16-8	3-Methyl-3-(3-hydroxy-3-methylbutoxy) butanol	1.1		
24851-98-7	3-Oxo-2-pentylcyclopentane acetate, methyl (Methyl dihydrojasmonate; Hedione)			1.8
1000364-43-9	4-Hydroxybenzyl alcohol. bis(tert-butyldimethylsilyl) ether			2.5
32210-23-4	4-tert-Butylcyclohexyl acetate (Vertenex)			1.9
110-93-0	5-Hepten-2-one, 6-methyl	1.5		1.6
18479-58-8	7-Octen-2-ol, 2,6-dimethyl	1.9		1.9
96-08-2	7-Oxabicyclo[4.1.0]heptane, 1-methyl-4-(2-methyloxiranyl)-			0.7

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