NOVEMBER 2024

TECHNICAL REPORT

Impact of 3D Printing on Indoor Air Quality in a University Dental School

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Executive Summary

Three-dimensional (3D) printing with resins is widely used in university dental schools. The printing and post-printing processes, however, are potential sources of airborne particulate matter (PM) and volatile organic compounds (VOCs) that may pose an exposure and potential health risk for users, especially vulnerable populations. This study monitored indoor air quality (IAQ), specifically airborne PM and VOCs, in a university dental school to evaluate the impact of resin 3D printing on IAQ. Studied locations included the main 3D printing area, grinding area, and post-processing bath area. Monitoring results showed grinding activity generated nanometer and micrometer sized particles, while resin printing did not contribute substantially to PM levels; however, the resin 3D printing area showed the highest total VOC levels and the most VOCs detected, indicating that the resin 3D printing emitted a complex mixture of VOCs. The most abundantly detected chemical was isopropanol, the solvent used for the post-printing process, and was likely dispersed from the bath area into the printing and grinding areas. This study showed that resin 3D printing and post-printing processes increased specific VOC levels in an educational setting during normal use, leading to exposure to chemical hazards, including irritants, carcinogens, and developmental toxins that could result in short-term irritation or long-term effects for occupants, especially those with respiratory diseases. Therefore, increased awareness and appropriate approaches are needed to identify specific hazards and to reduce potential exposure.

1.0 Introduction

Chemical Insights Research Institute (CIRI) has conducted a series of field studies investigating IAQ in educational settings with the use of 3D printing – the second of which addressed contamination resulting from the use of 3D printing with polymers in a dental school.[1] Studies to date indicate that 3D printing can contribute to elevated levels of PM and specific VOCs in indoor environments.

Vat photopolymerization, or resin 3D printing, builds an object using liquid resin that is cured or hardened by an ultraviolet (UV) light due to light activated polymerization. This 3D printing technology generates small-scale objects with precise details and fine and smooth finishes, which has led to its wide application in dental and medical fields. Due to the difference in printing mechanisms, resin 3D printing generates distinct emission profiles compared to material-extrusion 3D printing, which uses thermoplastics. CIRI previously monitored IAQ in a university dental school where resin 3D printers were routinely used.[1] Our study found that resin 3D printing contributed to the specific VOCs detected in the room, including those potentially associated with resin chemical makeup and the solvent used for post-processing treatment. Among detected VOCs, some were hazardous chemicals with health concerns, such as formaldehyde and acetaldehyde. On the other hand, PM size distribution showed mainly ultrafine particles (less than 100 nm in size) in the 3D printing room; therefore, more evaluations are needed to understand the impact of 3D printing emissions on educational indoor environments and the potential health concerns, especially for vulnerable people such as those with asthma.

In this study, CIRI visited a university dental school where resin 3D printing, post-processing units, and grinders are used routinely. Indoor VOC and PM levels were monitored in the rooms with targeted activities, and data was evaluated to determine the impact on IAQ.

2.0 Field Study Methods

2.1 SAMPLING AND ANALYSIS METHODS

Airborne particle concentration and size distribution were measured in real time with a NanoScan scanning mobility particle sizer (SMPS, TSI 3910) for 10 to 420 nm particles and an optical particle sizer (OPS, TSI 3330) for 0.3 to 10 µm particles. In addition, 37 mm polytetrafluoroethylene (PTFE) filter samples were collected for 1 hour at a flow rate of 1 L/min with duplicates. The filters were further extracted and analyzed by inductively coupled plasma-mass spectrometry (Agilent 7900) according to United States (U.S.) Environmental Protection Agency (EPA) methods 3051A and 6020 for metal elements.

VOC and aldehyde samples were collected using portable pumps calibrated to 0.2 and 0.5 L/min onto Tenax tubes and 2,4-dinitrophenylhydrazine (DNPH) cartridges, respectively. Furthermore, Tenax tubes were analyzed according to U.S. EPA TO-17 method for VOCs by using gas chromatography-mass spectrometry (Agilent 8890 and 5977B), and DNPH cartridges were analyzed according to U.S. EPA TO-11A method for low molecular weight aldehydes by using high-performance liquid chromatography (Agilent 1260 Infinity). VOC and aldehyde samples were collected for a one-hour duration. Target active sample volumes were 12 L for VOCs and 30 L for aldehydes. See Technical Brief 080 for more information about the analysis methods.[2] The limit of quantification (LOQ) was 0.5 µg/m^3 for each analyte. Active sampling was taken with duplicates. In addition, a real time portable gas analyzer, Fourier transform infrared spectroscopy (FTIR, Gasmet GT5000), was applied for a shorter sampling duration (30 min) when applicable. Since isopropanol is the work fluid for NanoScan SMPS, which was also the chemical used in the monitored site, particle monitoring was conducted at a different time from VOC monitoring to avoid a confounder in the analysis by the NanoScan SMPS introducing isopropanol into the VOC samples.

2.2 STUDIED MATERIALS AND SAMPLING SITES

The studied site was in the university clinic building, which is specifically for patient use. There were four resin 3D printers located in the printing area, which is used routinely for printing crowns, dentures, and bridges. The post-printing area held isopropanol baths and curing machines. In addition, monitoring was also conducted at the grinding area, where a dedicated exhaust system was installed. The printing area, post-printing area, and grinding area were located separately but connected. The sampling setups are shown in **Figure 1**. All samples were taken at the typical breathing zone for an average person and close to the target activities. Ambient outdoor VOC samples were also collected as a comparative baseline.

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

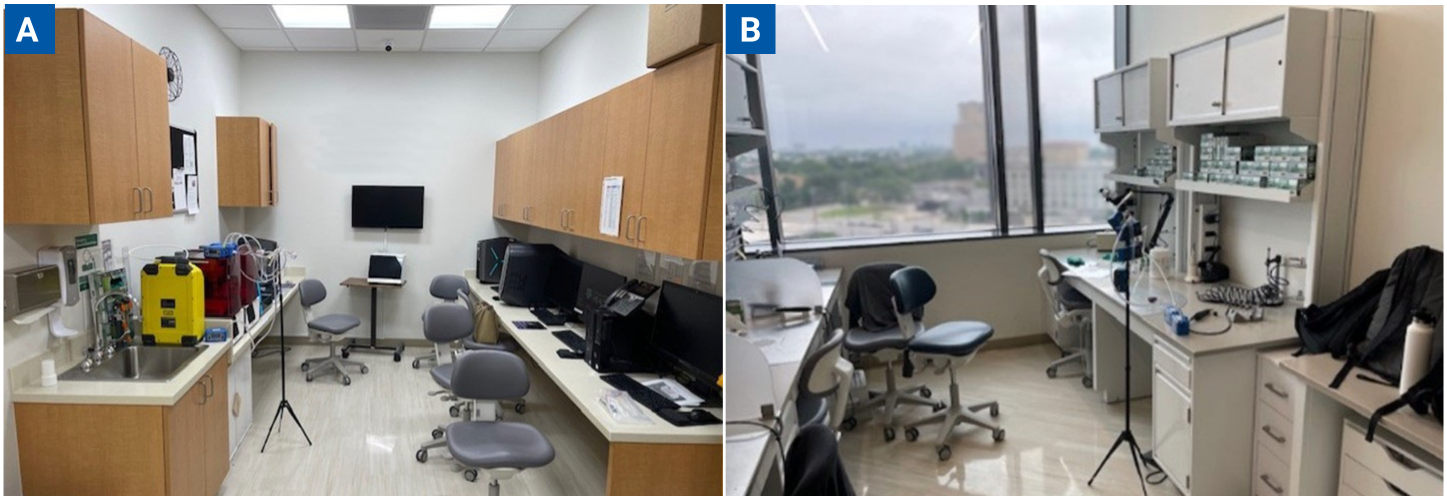

Figure 1: Monitoring sites with sampling instruments in the printing area (A) and grinding area (B).

3.0 Findings

3.1 INDOOR PARTICULATE MATTER LEVELS

Total particle concentrations for each monitoring location are shown in **Table 1**, where PM_{10} represents PM less than 10 μm in size and $PM_{2.5}$ represents PM less than 2.5 μm. The grinding area consistently had higher PM concentrations than the printing area, which indicated the introduction of PM from the grinding activity, even with a dedicated local exhaust system. Particularly, the PM_{10} level in the grinding area was approximately 23 times that in the printing area. However, both PM_{10} and $PM_{2.5}$ levels were below the National Ambient Air Quality Standards (NAAQS, 35 μg/m^3 for 24-hour $PM_{2.5}$ and 150 μg/m^3 for 24-hour PM_{10})[3] and World Health Organization (WHO) air quality guidelines (25 μg/m^3 for 24-hour $PM_{2.5}$ and 50 μg/m^3 for 24-hour PM_{10}). [4]

Table 1: Summary of total particle concentrations (mean ± standard deviation) in different sampling locations.

Sampling Location	Total number (#/cm^3)	PM10 (μg/m^3)	PM2.5 (μg/m^3)
Printing area	239±14	1.46±0.28	1.29±0.16
Grinding area	1054±160	33.1±7.8	3.99±0.99

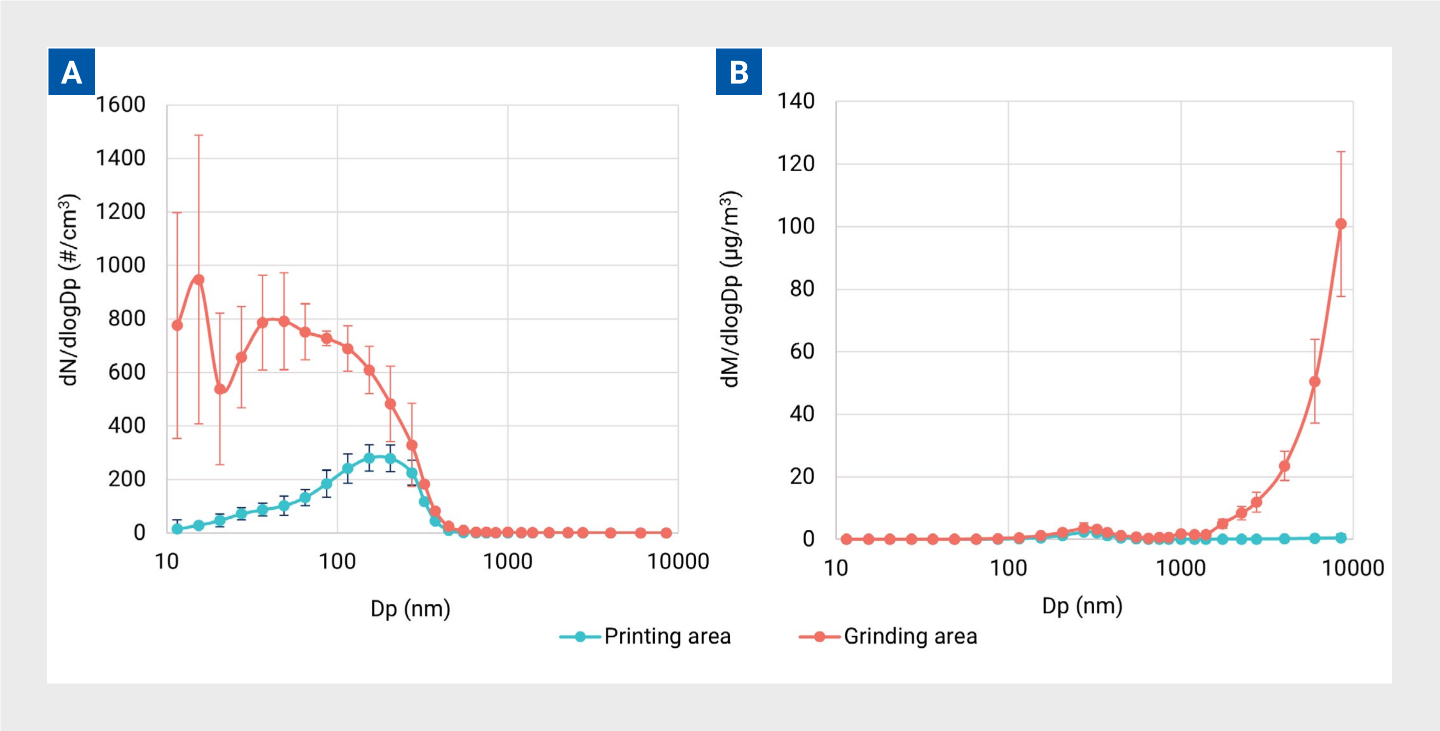

Figure 2: Particle size distributions for number (A) and mass (B) at each monitoring location. Error bars indicate standard error.

Since the health impacts also depend on the size of the particles, however, it is important to understand the size distributions of the particles. **Figure 2** summarizes the particle size distributions at the two monitoring locations. Both the printing area and grinding area were dominated by nanometer-sized particles according to particle number distribution, while the grinding area showed peaks of ultrafine particles (smaller than 100 nm), particularly around the 10 nm size range (**Figure 2A**). These small particles were likely emitted due to the mechanical grinding process and could have more health concerns than larger sized particles due to their high mobility. On the other hand, the grinding area showed higher concentrations of particle sizes between 1 µm and 10 µm (**Figure 2B**), which contributed to the higher mass concentrations of $PM_{2.5}$ and PM_{10} (**Table 1**). It should be noted that routinely monitoring $PM_{2.5}$ may not capture the ultrafine particles nor larger respirable dust generated from the grinding activity.

There were seven metal elements that were found above the detected limit and higher than the blank filters (**Table 2**), which included lithium (Li), beryllium (Be), chromium (Cr), nickel (Ni), zinc (Zn), cadmium (Cd), and thallium (Tl). Values without standard deviations indicate only one valid datapoint. Considering outdoor PM as a baseline, the printing area showed a slight elevation of Li and Ni concentrations, and relatively larger elevation of Zn concentration. In addition, the

Table 2: Summary of particle metal compositions normalized to volume of air sampled in different sampling locations.

Sampling Location	Li (ng/m³)	Be (ng/m³)	Cr (ng/m³)	Ni (ng/m³)	Zn (ng/m³)	Cd (ng/m³)	Tl (ng/m³)
Outdoor	0.29	0.16	30.5				
Printing area	0.71		26.2	0.23	36.9	0.01	0.01
Grinding area	3.04	0.22	45.1				

grinding area showed a moderate elevation in concentration of Li and Cr, which could have been from the grinding gears. Overall, metal concentrations in all monitoring locations were orders of magnitude lower than the reference levels in the occupational guidelines from the Occupational Safety and Health Administration (OSHA) and The American Conference of Governmental Industrial Hygienists (ACGIH®).

3.2 INDOOR VOLATILE ORGANIC COMPOUND LEVELS

Total volatile organic compound (TVOC) concentration was calculated by summing the toluene equivalent responses for the range of C_6 to C_{16}. **Figure 3** shows TVOC concentrations and the numbers of the VOCs detected from each monitoring location. The printing area showed the highest TVOC concentration, followed by the grinding area and ambient outdoor air. The printing area also showed the greatest number of VOCs detected compared to the grinding area and outdoors. These results indicate 3D printing is likely a source of VOCs in the printing area while the grinding activity did not contribute as much to TVOC levels. It should be noted that the TVOC calculation excludes very volatile or semi-volatile compounds, which also contribute to the indoor VOC levels.

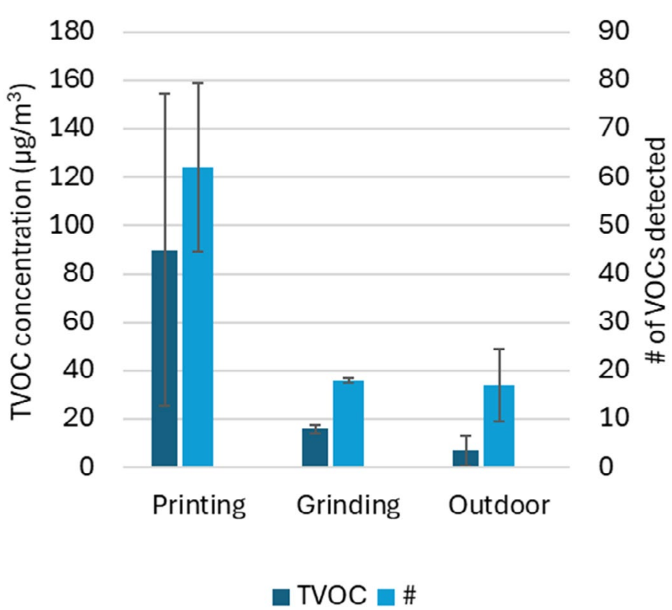

Figure 3: Averaged total VOC levels and number of VOCs detected for each sample location. Error bars indicate standard deviation.

The top ten highest detected VOCs in the printing area are listed in **Table 3** compared to the grinding area and outdoor air. Seven out of ten were detected previously from resin 3D printing and post-printing units in a chamber study.[5] Specifically, isopropanol was detected consistently with high concentrations indoors, which was attributed to the fact that it is used as the wash solvent in the post-printing process; and the bath area was connected to the printing and grinding area. 2-Butoxyethanol and 2-(2-ethoxyethoxy)ethanol were previously detected in a different dental school near the resin printers, which were likely associated with the resin or the printing emissions.[2] For the remaining VOCs that are potentially from resin printing, decamethylcyclopentasiloxane (D5) and acetic acid showed increased concentration in the printing area; 1-methoxy-2-propyl acetate, acetaldehyde, and ethylene glycol were unique for the printing area. **Appendix A** provides a complete list of VOCs detected above LOQ.

Table 3: Top ten detected VOCs from each monitoring location.

Chemical Ab-stracts Service (CAS) number	Chemical	Printing (µg/m³)	Grinding (µg/m³)	Outdoor (µg/m³)
67-63-0	Isopropanol	124	157	0.74
111-76-2	2-Butoxyethanol	37.5	11.5	
67-64-1	Acetone	22.0	23.4	
106-46-7	1,4-Dichlorobenzene	14.0	1.42	
111-90-0	Ethanol, 2-(2-ethoxyethoxy)-	13.8	3.57	
541-02-6	Cyclopentasiloxane, decame-thyl-	11.5	1.19	4.36
64-19-7	Acetic acid	10.1	7.39	6.94
108-65-6	1-Methoxy-2-propyl acetate	9.41		
75-07-0	Acetaldehyde	8.85		
107-21-1	1,2-Ethanediol (Ethylene gly-col)	8.38		

There were 29 chemicals of concern that were detected in this field study that are regulated by governmental agencies and industrial organizations to maintain good IAQ and occupants' health (**Table 4**). These chemicals include irritants, sensitizers, asthmagens, odors, carcinogens, developmental and reproductive toxins, and may cause adverse health impacts like inflammation, respiratory and neurotoxic symptoms, and cancer. All the chemicals of concern were detected in the printing area, and eight of them were also detected in the grinding area. This indicates that resin 3D printing is a potential source of hazardous chemicals. All hazardous chemicals are listed in standard method ANSI/CAN/UL 2904, except isopropanol, 1,4-dichlorobenzene, and 1-methoxy-2-propyl acetate[6]; however, all hazardous chemicals were below the recommended concentrations for indoor air.

Table 4: Chemicals of concern that were detected in the dental school and their associated health concerns.

CAS number	Chemical	Printing	Grinding	Target organ, system, disease endpoint
67-64-1	Acetone	X	X	
67-63-0	Isopropanol	X	X	*Eyes; respiratory system
111-76-2	2-Butoxyethanol	X	X	*Eyes and respiratory system
106-46-7	1,4-Dichlorobenzene	X	X	*Nervous and respiratory; alimentary systems (liver); kidney **Cancer
75-07-0	Acetaldehyde	X		*Eyes; respiratory system (sensory irritation) **Cancer
107-21-1	1,2-Ethanediol (ethylene glycol)	X		*Respiratory system; kidney; development **Developmental

Table 4: Chemicals of concern that were detected in the dental school and their associated health concerns.

CAS number	Chemical	Printing	Grinding	Target organ, system, disease endpoint
124-19-6	Nonanal	X		
124-13-0	Octanal	X		
104-76-7	1-Hexanol, 2-ethyl-	X	X	
95-63-6	Benzene, 1,2,4-trimethyl-	X		
108-88-3	Toluene	X	X	*Respiratory, nervous systems; eyes reproductive and development **Developmental
75-98-9	Propanoic acid, 2,2-dimethyl-	X		
80-62-6	Methyl methacrylate	X		
556-67-2	Cyclotetrasiloxane, octamethyl-	X	X	
112-31-2	Decanal	X		
71-36-3	1-Butanol	X		
66-25-1	Hexanal	X		
107-98-2	2-Propanol, 1-methoxy-	X		*Alimentary system (liver)
103-65-1	Benzene, propyl-	X		
50-00-0	Formaldehyde	X	X	*Eyes (sensory irritation) **Cancer
95-47-6	ortho-Xylene	X		*Nervous and respiratory systems; eyes
106-42-3	para-Xylene	X		*Nervous and respiratory systems; eyes
540-97-6	Cyclohexasiloxane, dodecame-thyl	X		
108-95-2	Phenol	X		*Respiratory system; eyes
78-93-3	2-Butanone (methyl ethyl ke-tone)	X		*Respiratory system; eyes
25265-77-4	2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (Texanol Isomer 1)	X		
98-86-2	Acetophenone	X		
98-82-8	Benzene, (1-methylethyl)-	X		**Cancer
123-42-2	2-Pentanone, 4-hydroxy-4-methyl-	X		

**California Office of Environmental Health Hazard Assessment (OEHHA) Reference Exposure Level (REL) Summary[7]
**OEHHA Proposition 65[8]

FTIR was used as a tool for screening chemicals and identifying any trends in the change of concentrations. FTIR was able to detect 24 out of the 65 VOCs identified from active sample analyses. **Appendix B** provides a list of the VOCs that were detected from both active sampling with sorbent tubes and real time FTIR; however, due to its high LOQ (parts per million level) and relative lower accuracy compared to active sampling, these results are viewed as informative as opposed to the quantitative analytical chemistry results. Given the limited time for field sampling, no active sampling was taken at the bath area. FTIR results show that the isopropanol concentration in the bath area was three times higher than the printing area and two times higher than the grinding area, which was likely due to the three areas being connected and the air being mixed by ventilation. In addition, FTIR results show that the grinding area had the lowest VOC levels in general followed by the printing area and the bath area.

4.0 Conclusions and Future Study

In this field study, we monitored airborne PM and VOC concentrations in a dental school at three locations where resin 3D printers, post-processing units, and grinders were routinely found. Our monitoring results showed that resin printing was less concerning regarding particle emissions, while grinding generated both ultrafine and micron-sized particles; however, the printing area showed greater numbers of VOCs detected and higher levels compared to the grinding area. The resin printing introduced or elevated numerous VOCs, including those with health concerns. Carcinogens detected include acetaldehyde, formaldehyde, 1,4-dichlorobenzene, and (1-methylethyl) benzene. Overall, no exceedance of concentration was found compared to recommended indoor reference levels.

Due to the impact of room conditions, resin types, and printer designs, the field study results tended to be specific for the studied location; therefore, additional field studies are needed to better understand the impact of resin 3D printing on IAQ in general. Specifically, measurements of room volumes and ventilation conditions would provide insights into the observed contaminant levels and trends.

5.0 REFERENCES

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7. California Office of Environmental Health Hazard Assessment. *OEHHA Acute, 8-hour and Chronic Reference Exposure Level (REL) Summary*, https://oehha.ca.gov/air/general-info/oehha-acute-8-hour-and-chronic-reference-exposure-level-rel-summary (2023).
8. California Office of Environmental Health Hazard Assessment. *The Proposition 65 List*, https://oehha.ca.gov/proposition-65/proposition-65-list (2024).

Appendix A: Complete VOC concentration results (average).

CAS number	Chemical	Printing area (µg/m³)	Grinding area (µg/m³)	Outdoor (µg/m³)
644-08-6	1,1'-Biphenyl, 4-methyl-	3.87		
107-21-1	1,2-Ethanediol (ethylene glycol)	8.38		
71-36-3	1-Butanol	1.86		
104-76-7	1-Hexanol, 2-ethyl-	3.90	2.66	2.64
108-65-6	1-Methoxy-2-propyl acetate	9.41		
111-87-5	1-Octanol	2.82		
77-68-9	2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (propanoic acid, 2-methyl-, 3-hydroxy-2,2,4-trimethylpentyl ester)	3.17		
25265-77-4	2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (Texanol Isomer 1)	0.62		
78-93-3	2-Butanone (methyl ethyl ketone)	0.70		

Appendix A: Complete VOC concentration results (average).

CAS number	Chemical	Printing area ($\mu g/m^3$)	Grinding area ($\mu g/m^3$)	Outdoor ($\mu g/m^3$)
53966-52-2	2-Octene, 4-ethyl-	3.72		
123-42-2	2-Pentanone, 4-hydroxy-4-methyl-	0.51		
13429-07-7	2-Propanol, 1-(2-methoxypropoxy)-	1.83		
10595-06-9	2-Phenoxyethyl methacrylate	3.34		
107-98-2	2-Propanol, 1-methoxy-	1.40		
868-77-9	2-Methyl-, 2-hydroxyethyl ester	1.67		
75-07-0	Acetaldehyde	8.85		
64-19-7	Acetic acid	10.1	7.39	6.94
67-64-1	Acetone	22.0	23.4	
75-05-8	Acetonitrile	3.82		
98-86-2	Acetophenone	0.58		0.89
107-02-8	Acrolein			4.78
98-82-8	Benzene, (1-methylethyl)-	0.52		
526-73-8	Benzene, 1,2,3-trimethyl-	3.48		
95-63-6	Benzene, 1,2,4-trimethyl-	3.57		
106-46-7	Benzene, 1,4-dichloro	14.0	1.42	
620-14-4	Benzene, 1-ethyl-3-methyl- (3-ethyltoluene)	2.92		
622-96-8	Benzene, 1-ethyl-4-methyl- (4-ethyltoluene)	1.69		
103-65-1	Benzene, propyl-	1.34		
65-85-0	Benzoic acid			0.80
95-16-9	Benzothiazole	3.55		
540-97-6	Cyclohexasiloxane, dodecamethyl	0.96		2.14
586-67-4	Cyclohexene, 4-methyl-1-(1-methylethenyl)-	1.54		
541-02-6	Cyclopentasiloxane, decamethyl-	11.5	1.19	4.36
556-67-2	Cyclotetrasiloxane, octamethyl-	2.23	1.33	2.79
541-05-9	Cyclotrisiloxane, hexamethyl-	3.13	0.70	0.71
112-31-2	Decanal	1.88		0.98
503-28-6	Diazene, dimethyl-	2.15		
107-46-0	Disiloxane, hexamethyl-		0.63	

Appendix A: Complete VOC concentration results (average).

CAS number	Chemical	Printing area ($\mu g/m^3$)	Grinding area ($\mu g/m^3$)	Outdoor ($\mu g/m^3$)
5989-27-5	D-Limonene	2.23		
112-40-3	Dodecane	0.64		
64-17-5	Ethanol	0.55	0.53	
111-90-0	Ethanol, 2-(2-ethoxyethoxy)-	13.8	3.57	
111-76-2	Ethanol, 2-butoxy-	37.5	11.5	
122-99-6	Ethanol, 2-phenoxy-	1.78		
50-00-0	Formaldehyde	1.21	1.52	
142-82-5	Heptane	0.95		
66-25-1	Hexanal	1.81		
142-62-1	Hexanoic acid	5.54		
7534-94-3	iso-Bornyl methacrylate	3.32		
67-63-0	Isopropanol	124	157	0.74
108-67-8	Mesitylene (1,3,5-trimethylbenzene)	5.63		
80-62-6	Methyl methacrylate	2.27		
124-19-6	Nonanal	6.25		5.00
4390-04-9	Nonane, 2,2,4,4,6,8,8-heptamethyl-	0.60		
871-83-0	Nonane, 2-methyl-	0.52		
124-13-0	Octanal	4.26		
95-47-6	ortho-Xylene	1.00		
106-42-3	para-Xylene	0.98		0.59
108-95-2	Phenol	0.83		0.53
75-98-9	Propanoic acid, 2,2-dimethyl-	2.89		
108-32-7	Propylene Carbonate			4.02
57-55-6	Propylene Glycol	3.74		
1066-42-8	Silanediol, dimethyl-	1.03	0.52	
629-59-4	Tetradecane		0.76	
108-88-3	Toluene	3.29	3.92	1.57
1120-21-4	Undecane	0.60		

Appendix B: VOCs detected by both active sampling with sorbent tubes and real time FTIR.

CAS number	Chemical	FTIR Identifier
95-63-6	1,2,4-Trimethylbenzene	0122
107-21-1	1,2-Ethanedithiol	0270
57-55-6	1,2-Propanediol (propylene glycol)	0188
108-67-8	1,3,5-Trimethylbenzene	0128
71-36-3	1-Butanol	0080
108-65-6	1-Methoxy-2-propyl acetate	0059
75-07-0	Acetaldehyde	0045
67-64-1	Acetone	0024
75-05-8	Acetonitrile	0222
541-02-6	Decamethylcyclopentasiloxane	0312
540-97-6	Dodecamethylcyclohexasiloxane (C12H36O6Si6)	0399
112-40-3	Dodecane	0273
111-76-2	Ethylene glycol monobutyl ether (2-butoxyethanol)	0293
50-00-0	Formaldehyde	0008
142-82-5	Heptane	0051
107-46-0	Hexamethyldisiloxane	0276
66-25-1	Hexanal	0213
142-62-1	Hexanoic acid	0209
67-63-0	Isopropanol	0049
5989-27-5	Limonene	0038
78-93-3	Methyl ethyl ketone	0046
556-67-2	Octamethylcyclotetrasiloxane	0405
95-47-6	ortho-Xylene	0014
1120-21-4	Undecane	0058

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