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RESEARCH ARTICLE

Three-Dimensional (3D) Printing in Non-Industrial Spaces: A Summary of Emissions Evaluations in 11 School Settings

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ABSTRACT

Background: Additive manufacturing or 3-dimensional (3D) printing is an emerging technology with increasing prevalence in non-industrial settings such as university and school settings. However, printers are often located in spaces not designed for this purpose.

Methods: 3D-printer use in 11 university and K-12 schools was evaluated by identifying emissions using area air sampling for volatile organic compounds (VOCs) and particle counting instruments (PCIs) measuring ultrafine particulate (UFP) and evaluating controls to reduce potential exposure. Ventilation in printer locations was also characterized.

Results: VOCs and UFP were identified during 3D printing. Best-practice recommendations were provided to school health and safety staff to protect users, including workers and students. Recommendations included installing and implementing engineering controls, administrative controls, and personal protective equipment (PPE) to minimize exposure to 3D printer emissions.

Implications: School health and safety staff can translate findings and recommendations for these 11 evaluations to identify 3D-printing areas on their campuses and use principles of industrial hygiene to protect workers and students and prevent the movement of emissions.

Conclusions: VOCs and UFP were detected during 3D printing. There were opportunities to improve health and safety practices and reduce potential exposure when using 3D printing technologies.

1 | Introduction/Background/Significance

Additive manufacturing, also called three-dimensional (3D) printing, is an emerging industry growing 19.5% in 2021 [1]. Due to decreasing costs, increasing accessibility, and improving technologies of small-scale 3D printers, non-industrial space usage such as schools, libraries, and makerspaces is leading to potential exposures in public populations and their use is anticipated to increase.

3D printer feedstocks may contain substances that have a history of causing adverse health outcomes. Styrene, benzene, formaldehyde, toluene, other volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons, metals, and ultrafine particles (diameter < 100 nm) have been measured from 3D printers in office and university settings [2–6]. Chronic adverse health outcomes from exposures to 3D printer emissions are difficult to assess because of their relatively short history of use. A health survey of 46 employees who regularly used 3D printers in various settings found that 59% had respiratory symptoms, including nasal congestion (12, 26%), rhinorrhea (9, 20%), itchy nose/throat/eyes (9, 20%), and cough (9, 20%), at least once per week in the past year, and that working more than 40 h per week with 3D printers was significantly associated with a respiratory-related diagnosis [7]. The previous history of adverse health outcomes and documented potential exposures necessitates improvements to 3D printing and preliminary guidelines with health and safety approaches to protect employee and student health. Some printer companies have addressed health and safety concerns in schools [8], but few studies have assessed emissions and the potential for occupational exposures to teachers, librarians, and other employees in these settings. There is also limited knowledge on cost-effective engineering controls to reduce 3D printing emissions in these spaces. Most participants did not use any personal protective equipment (PPE).

The purpose of this project was to evaluate cases of 3D printer emissions in non-industrial settings such as schools, libraries, and makerspaces, to characterize the potential for user exposures. To accomplish the goal, we observed work processes, practices, and conditions, including PPE use, measured 3D printing process emissions, and evaluated workspace ventilation and controls. Personal air sampling was not collected as part of these evaluations.

2 | Methods

2.1 | Participating Sites

Participating sites were different educational settings, including K–12 schools and universities. Spaces evaluated within these settings were traditional classrooms, school libraries, makerspaces, and research laboratories. Site leaders were informed about our efforts to study potential exposures in educational settings from presentations at conferences and webinars. Summaries of the participant sites, printers used, and print materials are presented in Table 1.

A variety of 3D printer brands and models were used across the sites. Printer technologies included fused filament fabrication (FFF), vat polymerization (VP), and PolyJet. In FFF printing, filaments are heated inside of a print head, and then become extruded from a computer-controlled nozzle to create an object one layer at a time to form an object. In vat polymerization printing, a vat of liquid photopolymer resin is cured by either an ultraviolet or laser light source onto a build platform one layer at a time [9]. For PolyJet printing, drops of a photopolymer resin are jetted or sprayed onto a build platform, and then cured with an ultraviolet light [10]. Print materials were either filament-based in FFF printers or photopolymer resins in VP and PolyJet printers. Filament materials included polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), and nylon. Bioprinting with alginate hydrogel was also observed in location D3.

2.2 | Instrumentation

For each location, we (1) determined the number and type of 3D printers and print material used; (2) conducted air sampling to characterize potential emissions of UFPs and VOCs from 3D printing; and (3) observed and assessed engineering controls, ventilation systems, and work practices and processes used in the 3D printing environment. Our evaluations focused on environmental air sampling as inhalation is the primary route of exposure.

2.2.1 | Area Air Sampling for Volatile Organic Compounds and Particle Emissions

Simultaneous area air samples for VOCs were collected during printing activities using:

TABLE 1 | Descriptions of locations and 3D printers.

Location	Description	Printer types (number)	Print materials
A1	University makerspace	FFF (5)	PLA
A2	University 3D printing lab	FFF (4)	PLA, ABS, nylon with carbon fiber
A3	University library makerspace	FFF (5)	PLA, ABS
A4	University classroom	FFF (3)	PLA
A5	University makerspace	FFF (1), SLA (1), PolyJet (1)	ABS (FFF and PolyJet), photopolymer resin (SLA)
B	Middle school classroom	FFF (4)	PLA
C	High school classroom	FFF (5, 3 in use)	PLA
D1	University makerspace	FFF (3)	PLA, TPU, support material
D2	University classroom	FFF (4, 1 in use)	PLA
D3	University chemistry lab	FFF (1), other (1)	ABS, alginate hydrogel
D4	University 3D printing lab	FFF (4)	PLA, ABS

Note: Unless noted, all printers were in use during the evaluation.
Abbreviations: ABS = acrylonitrile butadiene styrene, FFF = fused filament fabrication or fused deposition modeling, PLA = polylactic acid, SLA = stereolithography, TPU = thermoplastic polyurethane.

- Stainless steel thermal desorption (TD) tubes with three beds of sorbent material using NIOSH Manual of Analytical Methods (NMAM) 2549, modified for a 5-min desorption time, to screen for VOCs [11].
- Activated charcoal sorbent tubes using a modified NMAM 1501/1552 to quantify select VOCs identified by TD tube samples [11]. Specific VOCs were those found in the filament safety data sheets and those previously found in similar 3D-printing studies.

Airborne particle emissions were collected during printing activities using particle counting and sizing real-time, particle counting instruments (PCIs) that were within factory calibration at time of use:

- TSI Condensation Particle Counter (CPC) 3007 (TSI Inc. Shoreview, MN, USA) measuring particle concentrations (particles per cubic centimeter (p/cc)) in the size range of 10–> 1000 nm (nm), from 0 to 100,000 p/cc data-logging every 1 s.
- TSI NanoScan SMPS Nanoparticle Sizer 3910 (NanoScan; TSI Inc.) measuring ultrafine particle numbers and sizes (10–420 nm in diameter in various size ranges) from 100 to 1000,000 p/cc data-logging every 1 s.

Area air sampling and PCIs were placed within 3 ft from printing activities, or within 3 ft of at least one printer if multiples were in use simultaneously.

Airflow measurements of ventilation systems were measured using a TSI Alnor airflow capture hood (balometer, TSI Inc.). Pressurization between 3D-printing areas and adjacent spaces were assessed using either (1) a TSI VelociCalc Multi-Function Ventilation Meter 9565-P (VelociCalc, TSI Inc.) with pressure ports, (2) by calculating differences between measured room air supply and exhaust flow rates, or (3) by visual assessment using a smoke generation device (Wizard Stick, Zero Toys Inc.). This was done to see if emissions could migrate to other areas than the 3D-printing areas.

2.3 | Procedure and Data Analysis

For each location, we placed air sampling equipment and PCIs next to 3D printers during printing. We also placed a CPC in an adjacent hallway or room to evaluate particle emissions migrating outside of printing areas. For PCIs, data collection began before any printing activities to collect background particle concentrations. During sampling, we made written observations, noting printer start-ups, pauses/stops, and print completion, and activities occurring nearby that could interfere with measurements. Examples of activities that could affect measurements included particle-generating activities like wood cutting or chemical use not associated with 3D printing.

Ventilation flowrates in 3D printing areas were measured where possible, or provided by facility staff when measurements were not possible. Room ventilation rates, in air changes per hour (ACH), were calculated by measuring the volumetric flow rate of the air in cubic feet per minute (cfm) and room volume in cubic feet (ft^3). NIOSH scientists made observations of practices during 3D-printing activities and collected information about the space and 3D printers in use. Time-weighted average (TWA) concentrations were calculated for VOCs found in area air samples. Particle counting data were graphed and qualitatively reviewed for notable increases in particle emissions and cross-referenced with observations to determine if 3D printing activities were associated with increases in particle emissions.

3 | Results

3.1 | Area Air Sampling for VOCs and Particle Emissions

Table 2 summarizes VOCs identified and quantified at each location. The most commonly identified VOCs were isopropanol, acetone, and decamethylcyclopentasiloxane (D5). Ethanol, ethyl ether, and methylene chloride were also found in some 3D printing locations in quantifiable amounts. Pentadecane, tetradecane, n-butyl acetate, cyclohexane, ethylbenzene, and n-hexane were identified in air samples but at lower levels that were uncertain (concentrations between the limit of detection and the limit of quantification).

Data collected from PCIs showed instances of increasing particle concentrations during 3D printer start-up, printer malfunctions, or print failures. Printer malfunctions and failures included instances of clogged print nozzles, feedstock jams, malfunctions with base layers adhering to printer platform, and misaligned layers.

Figure 1 shows examples of particle concentration increases (circled in red) observed following printer start-up during four separate instances. All instances had at least one printer printing with PLA material. Location A3 also had one printer printing with ABS material, and D3 also had a printer printing with alginate hydrogel. Following the initial increase, particle concentrations declined but levels were above background as printing continued. Compared to background levels, particle concentrations increased from approximately 2- to 100-fold following printer start-up. In panel 3 (Location C, Day 1), a print failure occurred at approximately the same time as the printer start-up and particle concentrations increased at least 6-fold. In some instances, particle concentrations increased later in the day but could not be associated with the presence or absence of printer activity.

Figure 2 shows examples of particle concentration increases (circled in red) observed following printer malfunctions during two separate instances. All instances had at least one printer printing with PLA material. Location A2 also had one printer printing with ABS material. Following the initial increase, particle concentrations declined as printing continued. Compared to before the malfunction, particle concentrations increased from approximately 2- to 6-fold following printer malfunction. An additional example of a print malfunction occurred at approximately the same time as the printer start-up in Figure 1 panel 3.

TABLE 2 | Quantitative area air sampling results for VOCs, in parts per million (ppm).

Sample location	Day	Isopropanol	Acetone	D5	Ethanol	Ethyl ether	Methylene chloride
Location A1, near printers	1	0.98	[0.0069]	ND	—	—	—
Location A1, near printers	2	2.9	[0.013]	ND	—	—	—
Location A1, middle of room	1	0.16	[0.0098]	ND	—	—	—
Location A1, middle of room	2	0.28	[0.0077]	ND	—	—	—
Location A2, near 3 printers	1	0.24	ND	ND	—	—	—
Location A2, near 3 printers	2	1.4	[0.012]	ND	—	—	—
Location A2, near 1 printer	1	0.19	ND	ND	—	—	—
Location A2, near 1 printer	2	0.13	ND	ND	—	—	—
Location A3	1	1.1	[0.011]	[0.0031]	—	—	—
Location A3	2	1.3	[0.011]	[0.0022]	—	—	—
Location A4	1	2.5	0.041	[0.0028]	—	—	—
Location A5, between printers	2	1.1	ND	ND	—	—	—
Location A5, between printers	2	0.52	ND	ND	—	—	—
Location B, near teacher's desk	1	14	[0.033]	0.005	—	—	—
Location B, near teacher's desk	2	1.6	[0.013]	0.006	—	—	—
Location B, across the room from teacher's desk	1	15	[0.027]	[0.003]	—	—	—
Location B, across the room from teacher's desk	2	5.0	[0.014	0.005	—	—	—
Location C, near 3 printers at the back of class	1	3.5	0.014	0.0043	—	—	—
Location C, near 3 printers at the back of class	2	5.2	0.13	0.0046	—	—	—
Location C, near 1 printer and teacher's desk	1	1.1	[0.010]	0.0043	—	—	—
Location D1[a]	1	0.65	ND	ND	0.072	[0.0040]	ND
Location D1	2	2.6	ND	ND	0.063	[0.0084]	ND
Location D2	1	3.9	[0.0066]	[0.00082]	0.05	ND	ND
Location D3	1	0.63	0.063	ND	0.047	0.078	0.29
Location D4	1	2.5	[0.0087]	[0.0019]	ND	ND	ND

Sample location	Day	Pentadecane	Tetradecane	n-butyl acetate	Cyclohexane	Ethylbenzene	n-hexane
Location A1, near printers	1	—	—	—	—	ND	—
Location A1, near printers	2	—	—	—	—	ND	—
Location A1, middle of room	1	—	—	—	—	ND	—
Location A1, middle of room	2	—	—	—	—	ND	—
Location A2, near 3 printers	1	—	—	—	—	ND	—
Location A2, near 3 printers	2	—	—	—	—	ND	—
Location A2, near 1 printer	1	—	—	—	—	ND	—
Location A2, near 1 printer	2	—	—	—	—	ND	—
Location A3	1	—	—	—	—	ND	—
Location A3	2	—	—	—	—	ND	—
Location A4	1	—	—	—	—	ND	—
Location A5, between printers	2	—	—	—	—	ND	—
Location A5, between printers	2	—	—	—	—	ND	—
Location B, near teacher's desk	1	—	—	[0.013]	ND	—	—
Location B, near teacher's desk	2	—	—	ND	ND	—	—
Location B, across the room from teacher's desk	1	—	—	[0.011]	ND	—	—
Location B, across the room from teacher's desk	2	—	—	ND	ND	—	—
Location C, near 3 printers	1	—	—	—	ND	ND	—
Location C, near 3 printers	2	—	—	—	[0.015]	[0.0087]	—
Location C, near 1 printer and teacher's desk	1	—	—	—	ND	ND	—
Location D1[a]	1	[0.0015]	[0.0016]	—	—	—	ND
Location D1	2	[0.0032]	[0.0045]	—	—	—	ND
Location D2	1	ND	ND	—	—	—	ND
Location D3	1	ND	ND	—	—	—	[0.010]
Location D4	1	ND	ND	—	—	—	ND

Note: D5 = decamethylpentasiloxane, ND = not detected, — = not sampled, [] = concentrations in brackets are between the minimum detectable and minimum quantifiable concentrations and have more uncertainty.

[a] Equipment malfunction resulted in reduced air volume and potential underestimation of concentrations measured. Area air sampling results are not background corrected.

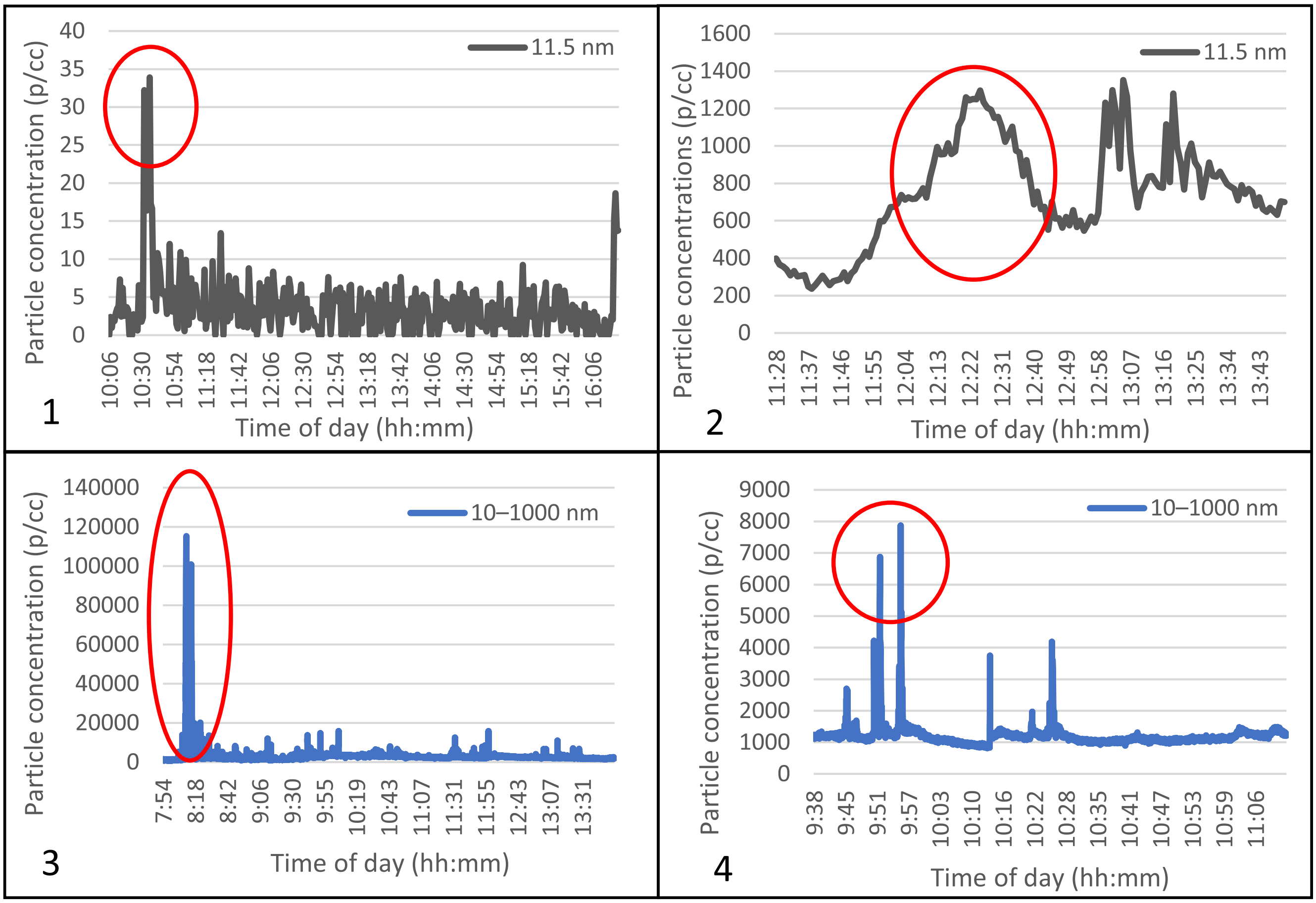

FIGURE 1 | Particle concentration increases (red) after observed printer start-up in (1) Location A3 (NanoScan, 11.5 nm particles), (2) Location A4 (NanoScan, 11.5 nm particles), (3) Location C Day 1 (CPC, 10–1000 nm particles), and 4) Location D3 (CPC, 10–1000 nm particles).

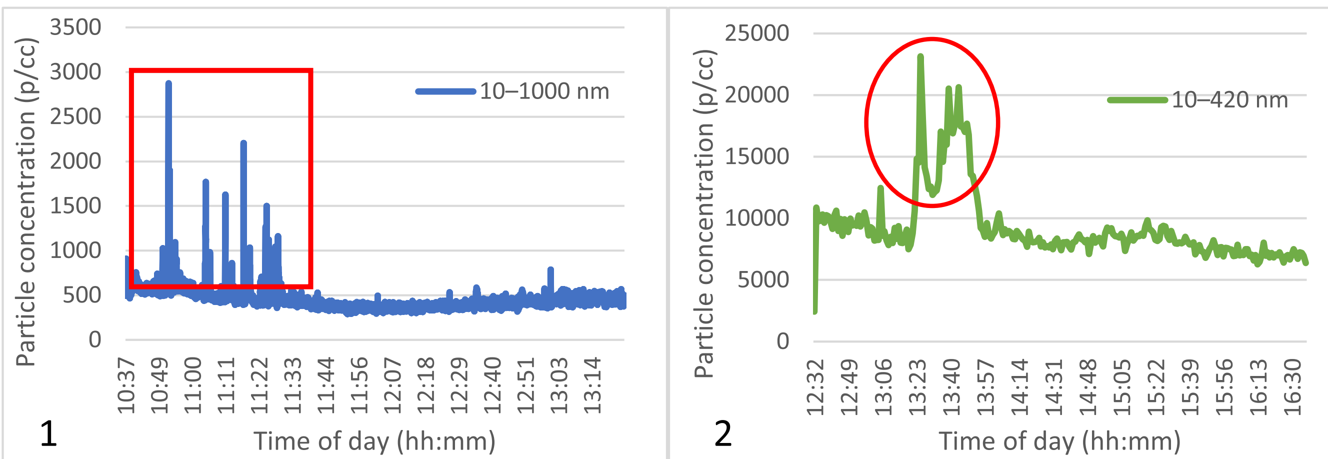

FIGURE 2 | Particle concentrations increases (red) after observed printer malfunctions in (1) Location A1 (CPC, 10–1000 nm particles) and (2) Location A2 (NanoScan, 10–420 nm particles).

Of the 11 locations assessed, 6 had observable particle concentration increases attributable to a printer start-up or malfunction. Printer malfunctions occurred four times during the assessments. Location D (university) had no instances of particle concentration increases associated with printing in four of the five locations assessed.

3.2 | Ventilation and Controls

Of 11 locations assessed, 5 had a ventilation or enclosure controls designed or intended to control emissions from 3D printing (Table 3). These included local exhaust ventilation (LEV) hard-ducted to a printer exhaust (1 of 11 locations), custom-built

TABLE 3 | Ventilation system evaluation results.

Location	Total supply airflow (cfm)	Total exhaust airflow (cfm)	Room area ($feet^2$)	Air changes per hour (ACH)	Pressurization compared to adjacent area	Installed ventilation controls	Additional observations
A1	1405	1200	1460	2.1	Positive	None	Door open Windows closed
A2	2800	Unable to determine	4000	4.7	Negative	Enclosures (4 printers), exhausted outdoors	Doors closed Windows closed
A3	637	366	350	13	Positive	None	Door closed No windows
A4	1479	1636	900	12	Negative	Enclosures (3 printers), no exhaust	Doors open and closed Windows closed
A5	936	935	1400	4.7	Neutral	1 printer directly exhausted outdoors	Door closed Window closed
B	0	Unable to determine	2137	Unable to calculate	Neutral	None	Doors open and closed Windows closed
C	Unable to determine	Unable to determine	1200	Unable to calculate	Positive	Paint booth available, not used for printing	Doors mostly closed No windows
D1	Not evaluated	313	402	4.7	Negative	Enclosures (2 printers), no exhaust	Door closed No windows
D2	45	52	285	1.3	Negative	None	Door open No windows
D3	Not evaluated	2060	1540	6.2	Neutral	None	Doors closed Windows closed
D4	289	567	620	5.5	Negative	Enclosures (4 printers), exhausted outdoors	Doors closed No windows

enclosures that contained and exhausted 3D printing emissions (2 of 11 locations), or custom-built non-ventilated enclosures designed or intended to contain emissions during the printing process (2 of 11 locations). These custom-built, non-ventilated enclosure designs included a large metal filing cabinet and a large plastic containment with doors left open during printings.

Regarding the flow of room air compared to adjacent areas, 3 of the 11 locations were positively pressured compared to adjacent areas, 3 of the 11 locations were found to have neutral room air pressure, and almost half of the locations (5 of 11) were negatively pressured compared to surrounding areas. One location (Location B) was found to not have any airflow into the space, despite the setup for heating and cooling ventilation.

More than half of the locations (6 of 11) had less than 6 air changes per hour in the 3D printing space (Table 3). Locations A3, A4, and D3 had air changes per hour ranging from 6.2 to 13. Locations B and C were not able to be calculated, which was either due to the ventilation system being inaccessible for measurements (Location C), or the ventilation system not operating at the time of the assessment (Location B).

3.3 | Work Processes, Practices, and PPE

Work processes, practices, and PPE use varied at each location. At 8 of 11 locations, safety data sheets (SDSs) were not available for print materials when requested. Over half of the locations had PPE requirements for 3D-printing activities (7 out of 11 locations), which was often only safety glasses. One location required safety glasses, a flame-retardant lab coat, long pants, closed-toed shoes, and nitrile gloves due to other chemical activities occurring in the lab. In most instances (5 out of 7), PPE requirements were followed by students and workers. Hazard communication signage was also displayed in seven locations, indicating that PPE was required to enter the location or worn for 3D printing activities.

We observed that students or workers remained in the 3D printing areas during printing in all the locations, remaining at workstations near printers and enclosures to monitor the printing progress and malfunctions, or to perform normal work activities.

4 | Discussion

Air sampling results showed that printer start-ups and failures were likely sources of potential exposures to ultrafine particulate (UFP), as seen in PCI results from our study (Figures 1 and 2) and in agreement with other studies [2, 12–17]. Results from PCIs in location D3 supported the hypothesis that print failures and start-ups could be sources of potentially higher exposures to UFP. PCI results in the location D4 did not show increases during the start-up of four 3D printers; this could have been attributed to the use of enclosures that were exhausted outdoors for all printers.

Measured as TWA concentrations over a full shift (typically 8 h), occupational exposure limits (OELs) are the highest level of exposure an average worker may be exposed to without incurring the risk of adverse health effects. While area air samples cannot be compared directly to OELs, we measured VOC concentrations orders of magnitude lower than the relevant OEL at all locations. The highest concentrations of acetone measured was 0.13 ppm (ppm) compared to the lowest OEL established by NIOSH of 400 ppm, a difference of three orders of magnitude; similarly, isopropanol, and ethanol were found two and five orders of magnitude below their lowest OELs, respectively. The highest concentration of acetone was measured at location C with no LEV (297 min), isopropanol was at location B with no LEV (347 min), and ethanol was Location D1 with enclosures that were not exhausted (234 min). For each location, participants conducted 3D-printing for the longest time that was typical. We collected air samples for the entire time of 3D-printing activities, ranging from 89 to 452 min (mean 289 min).

Isopropanol has been identified in other filament-based printing studies [3, 18, 19]. However, other sources could have contributed to the concentrations measured: isopropanol was used to clean printer beds and used in two of the PCIs. Acetone has also been found in previous studies [18–21] and is a common solvent in household and personal care products. Decamethylpentasiloxane was found in multiple locations but is a common ingredient in personal care products [22] and has not been found in other studies on 3D-printing emissions. Ethanol was found in several locations in facility D and has been noted in another study [14]. One sample collected at location D3 found quantifiable but low levels of methylene chloride, which is categorized as an occupational carcinogen [23]. Location D3 is a university chemistry lab; methylene chloride as a common solvent and liquid for chemical analyses and is not likely associated with this 3D-printing activity. Ethyl ether has not been found in other chamber or field studies and may be from the lab setting or an activity occurring nearby. The other VOCs that we measured that were detectable but not quantifiable may have come from 3D printing emissions or other VOC sources in the room, such chemical storage, new furniture and carpets, and other products used in makerspace and hobby settings [24]. While we documented other activities occurring in sampling locations, it was not definitive where these VOCs were emitted from.

For our study, we used a sampling strategy to pair PCIs evaluating UFP number and size concentrations with air samples analyzed for VOCs that are likely associated with 3D printing with filaments and resins. Using this strategy, along with worker and workplace observations, the results from this evaluation suggest a low potential for exposures significant to health in the air from 3D printer emissions. However, this and other studies show that UFP and VOCs can be emitted from filament-based printers. Research is lacking on health hazards from exposure to emissions from 3D printers. Given the results presented above, effective engineering controls and safe work practices could be used to lower potential exposures to 3D printer emissions.

Printer model, filament characteristics, and printer settings can play a role in emissions. Both PLA and ABS filaments were used at locations in this study. Studies have found that ABS filaments may emit higher concentrations of UFP compared to PLA filaments [25]. PLA filaments are preferred because of their potential as lower emitters. Although not measured in this study, ABS filaments are also more likely to emit VOCs of concern, such as benzene or styrene [2, 12, 14, 15].

While some locations evaluated, such as locations B, C, and D2 were not traditional "laboratories," these locations could be considered laboratories since chemicals or activities were used that can generate chemical emissions. The air change rates we calculated in most locations (A1, A2, A5, D1, D2, and D4) were below recommendations of at least 6–10 air changes per hour for laboratory spaces, as recommended by the National Research Council [26]. However, some of the 3D printing activities, such as those in A2 and D4 were in an enclosure exhausted to the outdoors.

Maintaining negative airflow pressurization for 3D printing spaces is preferred to prevent migration of VOCs, UFP, and odors from moving out of the areas. In locations where we were able to evaluate the ventilation systems, we found some labs were positively pressured compared to surrounding areas. This means that air flowed out of the location into adjacent areas. A better practice is to maintain the 3D-printing spaces as negatively pressured compared to other areas so that air flows into the location and reduces the possibility of unnecessary exposures to occupants of adjacent areas.

We observed inconsistences in work practices and the implementation of hazard communication that may contribute to unnecessary exposures. For example, user workstations were near 3D printers during printing in some locations, SDSs were not always readily available for print materials, and standard operating procedures for 3D printing activities were not available (hazard communication). Additionally, we noted instances where PPE was required to be used in a location, and both students and workers were not following PPE requirements, or there was confusion about what PPE was required. Positioning 3D printers as far away as possible from people during printing and training users on how to safely use 3D printers, available controls, and hazards from use could help reduce unnecessary exposures.

Anecdotally, university health and safety personnel at both university sites explained that 3D printing activities were widespread throughout campus and often unknown to health and safety staff. K-12 locations typically had a better understanding of 3D printer locations and activities.

5 | Implications for School Health Policy, Practice, and Equity

The field of industrial hygiene strives to control exposures to hazards in the workplace to protect workers. The hierarchy of controls is a framework to determine which actions will best control exposures [27]. Engineering controls can reduce or prevent hazards from coming into contact with workers, and include modifying the workspace, equipment, barriers, and ventilation. Administrative controls establish work practices and processes that reduce exposures to hazards. Additionally, PPE is generally recommended when engineering and administrative controls to reduce exposures to a desirable level are not feasible or available.

While air sampling results suggest potential for low level exposures to VOCs and UFP, steps can be taken to prevent unnecessary exposures to these, control odors, and reduce emissions moving out of printing spaces. The following considerations and supporting documents can be incorporated into plans for health and safety professionals to consider when planning for the use of 3D printers. These materials provide information for all users of 3D printers, including teachers, librarians, and students. These considerations are based on general findings from our evaluations at these and other non-industrial locations and are organized based on the hierarchy of controls [27].

The NIOSH Approaches to safe 3D printing: a guide for makerspace users, schools, libraries, and small businesses [9] describes the use of an enclosure with LEV, which may include a laboratory fume hood or a bench-top ventilated enclosure, as an engineering control to capture and remove UFP and chemicals emitted by 3D printers. LEV may exhaust printer emissions directly outdoors or through a high-efficiency particulate air (HEPA) filter to remove particles prior to exhaust or recirculation. Locations A2 and D4 used enclosures that were aligned with this approach. PCIs at location D4 did not show increases in UFP following startup. At location A2, PCIs measured increases in UFP when enclosures were opened following a printer malfunction. Some researchers have shown that the use of a simple ventilated enclosure with an exhaust fan and attached HEPA filter reduced the emissions released to the room by 97% [28]. The enclosure used in location D1 is another example of an enclosure for 3D printers, which would more effectively capture emissions if ported and connected to an exhaust system. Examples of a ventilated enclosure designed to contain 3D-printer emissions from multiple printers were observed in location D4.

Another option for controlling 3D printing emissions is connecting LEV to the printer print heads [29] or effectively positioning LEV near the printers to capture emissions. If there are concerns about VOC emissions or odors, consider adding gas and vapor filters to the exhaust of these ventilation control systems. For 3D printers placed in ventilated enclosures, users should wait for printer emissions to be removed from the ventilated enclosure before opening the enclosure. The amount of time required for printer emissions to be removed is based on the size of the enclosure and how much airflow is exhausted. Users should also wait for the emissions to decrease before approaching a printer that has malfunctioned.

Other steps can be taken to adhere to best-practice and prevent potential exposures, control odors, and reduce emissions in the printing locations. For example, starting a print when there are fewer occupants in the area or leaving the area following startup. Starting the printer head heating without filament (if possible), cleaning the nozzle after printing of residual filament, and setting a lower operating temperature for the printer nozzle when possible are additional printing strategies that can help lower printer emissions [28, 30]. Research has also shown that certain filaments and print materials emit more VOCs and UFP than others. For example, ABS-based filaments have been shown to emit more UFP than PLA-based filaments [28]. Choosing lower-emitting filaments can also reduce the potential and amount of exposure.

NIOSH's Advanced Manufacturing webpage has 3D printing guidance documents for additional information. For example, NIOSH developed printable posters including one specific to filament-based 3D printing that cite health and safety concerns with different control options and other information to reduce exposure to potential hazards, as well as a one-page guidance for plastic filament. NIOSH also recently released guidance titled Approaches to safe 3D printing: a guide for makerspace users, schools, libraries, and small businesses [9].

5.1 | Limitations

Characterizations of 3D printer use in each space only evaluated a single point in time; we were only able to assess VOC and UFP levels and conditions on the days of the evaluation. Several variables, including the number of printers running, duration of printing, filaments used, changes in printer settings, and number of start-ups, failures, and malfunctions can affect VOC identity and concentrations, and UFP concentrations. Conditions outside of the print environment (e.g., VOCs from building materials, UFPs from outside activities) were not accounted for. Other filaments (i.e., nylon filament) and photopolymer resins were available for use but were not the focus of this study.

We did not conduct personal sampling for VOCs and UFP as this was an exploratory pilot project characterizing 3D printing in these settings. Therefore, we were not able to determine actual exposure for users of these 3D printers and provide a comparison to an OEL. Furthermore, we did not ask about health effects associated with 3D-printer use.

PCIs could have been affected by the location of the printers in the labs, the location of the sampling equipment, the relatively small number of printers used in a large space, other particle-generating activities in the area, and the use of effective engineering controls. Because of the small sample size and locations differing in these variables and in controls implemented, we were not able to compare emissions by these variables affecting VOCs and UFP. Engineering controls were sparse and sometimes not used optimally, making it difficult to determine how much these controls reduced printer emissions.

Additionally, our presence could have changed typical 3D-printing procedures and practices. The sampling results only reflect conditions on the days we sampled, and emissions could be higher or lower on other days.

6 | Conclusions

Quantifiable amounts of some VOCs (including isopropanol, acetone, ethanol) were measured in air samples and UFP emissions were detected by PCI during 3D printing. The PCI results showed that printer start-ups and failures were likely sources of potentially higher exposures to UFP. To decrease the potential for exposures to students and workers, we recommended separating print spaces, using LEV such as ventilated enclosures, and administrative controls, such as implementing policies on allowable filaments and training on preventing exposures during 3D printing tasks.

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Ethics Statement

Preparation of this paper did not involve primary research or data collection involving human subjects, and therefore, no institutional review board examination or approval was required. This activity was reviewed by CDC, deemed not research, and was conducted consistent with applicable federal law and CDC policy (see e.g., 45 C.F.R. part 46, 21 C.F.R. part 56; 42 U.S.C. §241(d); 5 U.S.C. §552a; 44 U.S.C. §3501 et seq.).

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. Associates W, *Wohlers Report 2022 Finds Strong Industry-Wide Growth* (Fort Collins, CO: Wohlers Associates, 2022) accessed November 28, 2023, https://wohlersassociates.com/press-releases/wohlers-report-2022-finds-strong-industry-wide-growth/.

2. P. Steinle, "Characterization of Emissions From a Desktop 3D Printer and Indoor Air Measurements in Office Settings," *Journal of Occupational and Environmental Hygiene* 13, no. 2 (2016): 121–132, https://doi.org/10.1080/15459624.2015.1091957.

3. J. S. Youn, J. W. Seo, S. Han, and K. J. Jeon, "Characteristics of Nanoparticle Formation and Hazardous Air Pollutants Emitted by 3D Printer Operations: From Emission to Inhalation. Article," *Royal Society of Chemistry Advances* 9, no. 34 (2019): 19606–19612, https://doi.org/10.1039/c9ra03248g.

4. F. L. Chan, C. Y. Hon, S. M. Tarlo, N. Rajaram, and R. House, "Emissions and Health Risks From the Use of 3D Printers in an Occupational Setting. Article," *Journal of Toxicology and Environmental Health - Part A: Current Issues* 83, no. 7 (2020): 279–287, https://doi.org/10.1080/15287394.2020.1751758.

5. A. C. Hayes, J. Osio-Norgaard, S. Miller, G. L. Whiting, and M. E. Vance, "Air Pollutant Emissions From Multi Jet Fusion, Material-Jetting, and Digital Light Synthesis Commercial 3D Printers in a Service Bureau," *Building and Environment* 202, no. 3 (2021): 108008, https://doi.org/10.1016/j.buildenv.2021.108008.

6. N. Afshar-Mohajfer, C. Y. Wu, T. Ladun, D. A. Rajon, and Y. Huang, "Characterization of Particulate Matters and Total VOC Emissions From a Binder Jetting 3D Printer," *Building and Environment* 93, no. 2 (2015): 293–301, https://doi.org/10.1016/j.buildenv.2015.07.013.

7. F. L. Chan, R. House, I. Kudla, J. C. Lipszyc, N. Rajaram, and S. M. Tarlo, "Health Survey of Employees Regularly Using 3D Printers. Article," *Occupational Medicine* 68, no. 3 (2018): 211–214, https://doi.org/10.1093/occmed/kqy042.

8. Formlabs, "Guide to 3D printing in education," accessed February 5, 2024, https://formlabs.com/blog/guide-3d-printing-education/.

9. "Approaches to Safe 3D Printing: a guide for makerspace users, schools, libraries, and small business (DHHS (NIOSH)) (2023)".

10. Stratasys, "PolyJet Technology," accessed April 4, 2024, https://www.stratasys.com/en/guide-to-3d-printing/technologies-and-materials/polyjet-technology/#:~:text=PolyJet%203D%20Printing%20is%20an,transformed%20into%20a%20printable%20format.

11. "2003–154 NIOSH Manual of Analytical Methods 4th Edition (DHHS (NIOSH)) (2003)".

12. P. Azimi, D. Zhao, C. Pouzet, N. E. Crain, and B. Stephens, "Emissions of Ultrafine Particles and Volatile Organic Compounds From Commercially Available Desktop Three-Dimensional Printers With Multiple Filaments. Article," *Environmental Science and Technology* 50, no. 3 (2016): 1260–1268, https://doi.org/10.1021/acs.est.5b04983.

13. Y. Kim, C. Yoon, S. Ham, et al., "Emissions of Nanoparticles and Gaseous Material From 3D Printer Operation. Article," *Environmental*

Science and Technology 49, no. 20 (2015): 12044–12053, https://doi.org/10.1021/acs.est.5b02805.

14. A. B. Stefaniak, R. F. Lebouf, J. Yi, et al., "Characterization of Chemical Contaminants Generated by a Desktop Fused Deposition Modeling 3-Dimensional Printer," *Journal of Occupational and Environmental Hygiene* 14, no. 7 (2017): 540–550, https://doi.org/10.1080/15459624.2017.1302589.

15. B. Stephens, P. Azimi, Z. El Orch, and T. Ramos, "Ultrafine Particle Emissions From Desktop 3D Printers," *Atmospheric Environment* 79 (2013): 334–339, https://doi.org/10.1016/j.atmosenv.2013.06.050.

16. J. Yi, R. F. LeBouf, M. G. Duling, et al., "Emission of Particulate Matter From a Desktop Three-Dimensional (3D) Printer," *Journal of Toxicology and Environmental Health—Part A: Current Issues* 79, no. 11 (2016): 453–465, https://doi.org/10.1080/15287394.2016.1166467.

17. Q. Zhang, M. Pardo, Y. Rudich, et al., "Chemical Composition and Toxicity of Particles Emitted From a Consumer-Level 3D Printer Using Various Materials," *Environmental Science and Technology* 53, no. 20 (2019): 12054–12061, https://doi.org/10.1021/acs.est.9b04168.

18. A. B. Stefaniak, A. R. Johnson, S. du Preez, et al., "Insights Into Emissions and Exposures From Use of Industrial-Scale Additive Manufacturing Machines. Article," *Safety and Health at Work* 10, no. 2 (2019): 229–236, https://doi.org/10.1016/j.shaw.2018.10.003.

19. A. B. Stefaniak, A. R. Johnson, S. du Preez, et al., "Evaluation of Emissions and Exposures at Workplaces Using Desktop 3-Dimensional Printers. Article," *Journal of Chemical Health and Safety* 26, no. 2 (2019): 19–30, https://doi.org/10.1016/j.jchas.2018.11.001.

20. L. Bravi, F. Murmura, and G. Santos, "Additive Manufacturing: Possible Problems With Indoor Air Quality," *Procedia Manufacturing* 41 (2019): 952–959.

21. N. Dias Pinheiro, R. Teixeira Freire, J. A. M. Conrado, A. D. Batista, and J. F. da Silveira Petruci, "Paper-Based Optoelectronic Nose for Identification of Indoor Air Pollution Caused by 3D Printing Thermoplastic Filaments," *Analytica Chimica Acta* 1143 (2021): 1–8, https://doi.org/10.1016/j.aca.2020.11.012.

22. Council AC, "Silicones," accessed December 1, 2023, https://www.americanchemistry.com/chemistry-in-america/chemistries/silicones.

23. NIOSH, "Occupational Cancer—Carinogen List. U.S. Department of Health and Human Services, Centers for Disease Con," accessed March 13, 2023, https://www.cdc.gov/niosh/topics/cancer/npotocca.html.

24. USEPA, "Volatile Organic Compounds' Impact on Indoor Air Quality," accessed December 12, 2024, https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality.

25. C.-L. Tang and S. Seeger, "Systematic Ranking of Filaments Regarding Their Particulate Emissions During Fused Filament Fabrication 3D Printing by Means of a Proposed Standard Test Method," *Indoor Air* 32, no. 3 (2022):1–12, https://doi.org/10.1111/ina.13010.

26. Council NR, "Prudent Practices in the Laboratory," 2011, https://nap.nationalacademies.org/catalog/12654/prudent-practices-in-the-laboratory-handling-and-management-of-chemical.

27. NIOSH, "Hierarchy of Controls. Centers for Disease Control and Prevention," accessed March 8, 2023, https://www.cdc.gov/niosh/topics/hierarchy/default.html.

28. "Measuring and Controlling Emissions From Polymer Filmanet Desktop 3D Printers (Health and Safety Executive) (2019)".

29. K. L. Dunn, D. Hammond, K. Menchaca, G. Roth, and K. H. Dunn, "Reducing Ultrafine Particulate Emission From Multiple 3D Printers in an Office Environment Using a Prototype Engineering Control," *Journal of Nanoparticle Research* 22, no. 112 (2020): 1–11, https://doi.org/10.1007/s11051-020-04844-4.

30. T. R. Simon, W. J. Lee, B. E. Spurgeon, B. E. Boor, and F. Zhao, "An Experimental Study on the Energy Consumption and Emission Profile of Fused Deposition Modeling Process," *Procedia Manufacturing* 26 (2018): 920–928.