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Emissions from consumer fused deposition modelling 3D printers and their potential health impact

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SUMMARY
Particle and volatile organic compound (VOC) emissions from consumer level fused deposition modelling (FDM) 3D printers were characterized to assess possible hazards to the general public that utilize FDM 3D printers in personal residences, educational institutions and work environments. Tests employing a standardized emission chamber and data analysis protocol showed that printing produced high concentrations of ultrafine particles. Particle emission yields depended on the type of filament material, filament brand and extrusion temperature. The chemical composition of emitted particles was in some cases similar to the filaments, while in other cases particle composition did not match the filaments, indicating filament trace additives' role in particle formation. This could explain why particle emissions from different filament brands differed. Particle toxicity was assessed with various assays. Despite differences in intrinsic toxicity, possible toxicity of exposure was mainly driven by differences in particle emissions. Hazardous VOCs were also emitted from FDM printers.

KEYWORDS
3D printer; particle emission; volatile organic compound (VOC); toxicity

1 INTRODUCTION
FDM 3D printers build an object by extruding a thermoplastic filament through a heated nozzle and depositing it onto a plate in layers. As these printers increase in popularity with the general public, concern of potential health impacts of emissions from 3D printers has been raised since they are often found in small-scale indoor environments and public spaces, leading to potential exposure to vulnerable populations, such as children. Studies have recorded high levels of particle and VOC emissions from 3D printers that depend on operating conditions and environmental setup. However, a systematic characterization of particle emissions using a standard method has been lacking, and the mechanism of particle formation from 3D printers is unclear. Toxicity studies on FDM-generated particles are also limited. In this study, we performed a comprehensive assessment of emissions from FDM 3D printers, including characterization of particle and VOC emission yields (emission per mass of filament consumed) via chamber experiment, and estimations of composition and potential toxicity.

2 METHODS

Characterization of emissions was done using a 1 m^3 stainless steel chamber, designed and evaluated following the ASTM standard D6670 (ASTM, 2013) and UL GREENGUARD Certification 2823 (UL, 2014). Dry particle and VOC free air was continuously supplied in the chamber at 16.7 L min^{-1}. Particle concentrations and size distributions were measured with a suite of instrumentation. VOC and aldehyde samples were collected onto solid sorbent cartridges and then analysed by gas chromatography-mass spectrometry (GC/MS) and high-performance liquid chromatography separately, following US EPA Compendium Method TO-11A and 17 (USEPA, 1999a; b) and ASTM standard D6196 (ASTM, 2009). Test procedures and calculations of emissions followed BAM (2012), developed for testing emissions from laser printers. Particle composition was determined by aerosol mass spectroscopy and filament/particle composition by pyrolysis GC/MS. Toxicity tests focused on particle oxidative potential or oxidative stress responses. Particles were collected onto Teflon™ filters during chamber experiments and assessed with various cellular and acellular assays on filter extracts.

3 RESULTS and DISCUSSIONS

In general, particle number concentration peaked at the beginning of the printing process, then dropped and reached a steady state as printing continued. Concentration profiles and total emissions largely depended on filament material. For the most widely used feedstock material, acrylonitrile butadiene styrene (ABS) generally emitted vastly more particles than polylactic acid (PLA). For the same filament material, some specific filament brands generated significantly higher emissions when operating under identical conditions, indicating minor filament additives might drive particle emissions. In addition, extrusion temperature also affected particle emissions following an exponential relationship. Particles from PLA, the lowest emitting filament, were chemically similar to filament monomers, whereas highest emitting ABS filament produced particles chemically dissimilar to the bulk filament. Toxicity tests indicated that particles were largely insoluble, since filtration of particle liquid extracts removed all toxic responses. All toxicity tests showed responses to FDM-emitted particles, with contrasting responses on a per surface area or mass basis for filaments of different composition. However, particles emitted from ABS were more toxic than that of PLA on a per print time or per print object mass (or filament consumed) basis. VOC emissions varied depending on filament material; total VOC emission rates were higher for ABS than PLA. Among the various detected VOCs, many have known potential hazards; such as styrene from ABS filaments and caprolactam from nylon filaments. Concentrations of certain hazardous species may exceed recommended levels when printing in small spaces with minimal outdoor air exchange. Therefore, strategies to reduce exposure include printing with low-emitting filaments, lowering extrusion temperature, enhancing outdoor air ventilation rates, or providing local exhaust.

4 CONCLUSIONS

Characterization of emissions from 3D printers showed major controlling factors included filament material, filament brand and extrusion temperature. Overall, particle emission rates from high emitting materials like ABS were comparable to that from laser printers, for which standards have been developed. Total VOC emission rates were on average lower than laser printers, but numerous individual VOCs were detected. Emission results indicate that steps should be taken to minimize exposure in indoor environments.

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