Author Manuscript
Author Manuscript
Author Manuscript
Author Manuscript

HHS Public Access
Author manuscript
J Occup Environ Hyg. Author manuscript; available in PMC 2023 March 17.

Published in final edited form as:
J Occup Environ Hyg. 2021 ; 18(10-11): 489–494. doi:10.1080/15459624.2021.1976413.

Nano- and microplastics in the workplace

Vladimir Murashov,
Charles L. Geraci,
Paul A. Schulte,
John Howard
Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Washington, DC

Keywords

Exposure; hazards; microplastics; nanoplastics; occupational; workplace

Introduction

The on-going COVID-19 pandemic has resulted in a dramatic increase in the use of N95 respirators, barrier face coverings, disposable gloves, gowns, and other measures to control the spread of SARS-CoV-2. For example, population-based estimates suggest that over seven billion facemasks, which translates to 21,000 tons of synthetic polymer, are used daily in the world in response to the COVID-19 pandemic (Hantoko et al. 2021). After use, these products end up in the synthetic polymer environmental waste stream and contribute to the growing problem of plastic pollution at an estimated rate of about 40% of plastic demand (Lau et al. 2020). Plastic litter in the environment breaks down to plastic fragments, which have been found in air, water, and food (Gigault et al. 2018; Mitrano 2019; Lim et al. 2021). Small particles of plastics are often referred to as microplastics (plastic particles with any dimension between 1 micrometer and 1,000 micrometers [ISO 2020]) and nanoplastics (plastic particles smaller than 1 micrometer [ISO 2020]). Polyethylene and polypropylene are the most commonly found types of plastic in aquatic environments and soil matrices (Yang et al. 2021). Nano- and microplastics (NMP) can be formed incidentally through environmental and mechanical degradation. Incidental NMP can be also generated through condensation of molecular species, for example, during heating or burning of plastics. Different pathways for generation of these particles produces incidental NMP of varying morphology and chemical composition, thus leading to varying biological activity ranging from activation of transient inflammatory response and interference with physiological functions to immunosuppression and carcinogenesis (Huaux 2018; Prata 2018). Manufactured NMP can be made intentionally for use in industrial processes, for example, as feedstock for powder-bed and multi-jet fusion 3D printers.

✉**CONTACT** Vladimir Murashov, vmurashov@cdc.gov, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, 395 E Street, SW, Suite 9200, Washington, DC 20201, USA.

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

Human exposure to NMP particles through inhalation and ingestion has raised concerns about their potential adverse health effects and has led to calls for monitoring the environment and food for plastic pollution (Alexy et al. 2020). At the 2019 Global Summit on Regulatory Science, regulatory bodies from ten countries identified a number of knowledge gaps, including a lack of suitable and validated analytical methods for sampling, identification and quantification of NMP and paucity of hazard and fate data, which hinders regulatory risk assessments (Allan et al. 2021). Since 2019, progress has been achieved in developing new analytical techniques for characterization of NMP in different environmental media (Castelvetro et al. 2021; Velimirovic et al. 2021; Yang et al. 2021). This paper discusses potential health hazards and exposure mitigation to NMP in the workplace, along with a description of recent work being conducted by NIOSH.

Potential workplace exposure to nano- and microplastics

While recent public attention to the plastic pollution and the presence of NMP in food, water, and air raised questions about potential adverse health effects of NMP in the general population, a critical issue from an occupational health perspective is whether there is exposure of workers to NMP and how it might occur. In the workplace, the main exposure route of concern is inhalation of particles suspended in the air. Unlike general population, which could be exposed to low-level concentrations of NMP in the air (ca. 50 particles per m^3 [Dris et al. 2017]), workers can be exposed to many orders of magnitude higher concentrations (ca. 4×10^{10} particles per m^3 for extrusion 3D printers [Stefaniak et al. 2019a]). Since workers are also a subset of the general population, they could be exposed to short-term high concentration of NMP in the workplace and to long-term low concentrations of NMP outside of work (NIOSH 2021a).

Particles of nano- and microplastics can become airborne and consequently lead to inhalation exposure during mechanical and environmental degradation of plastic goods and during manufacture and processing of plastics through condensation aerosol formation. *Mechanical and environmental degradation* of plastic goods can lead to potential exposures to nano- and microplastics among workers in the waste management and recycling operations (Wohlleben et al. 2013). Degradation of carpets and other synthetic fiber products can produce airborne fibers considered NMP (Dris et al. 2017) with potential for exposure among office/teleworkers and custodial staff. In the on-going pandemic, increasing use of face masks and respirators prompted studies of the presence of NMP on surfaces of respiratory protection equipment (Han and He 2021). At this time, it is unknown whether these NMP can be shed during use of these devices and result in toxicologically relevant NMP exposures to workers in healthcare and service industries.

Other examples of workplace processes generating dusts and potentially leading to worker exposure to NMP are sanding, machining, and cutting of polymer fibers such as nylon flocking (Burkhart et al. 1999) and of plastic products and composites (Zimmer and Maynard 2002; Starost and Njuguna 2014; Ding et al. 2017; Kang et al. 2017; Lee et al. 2020; Shin et al. 2020) and production of polyvinylchloride (PVC) piping and plastics.

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

In *the manufacture and processing of plastics*, polymer fume containing nucleation-based NMP can be generated during the following manufacturing activities: (1) the production of polymers as beads or powder when polymer is made and then extruded and chopped for further processing; (2) the production of plastic products such as injection molding, blow melt bottle making and 3D printing from melting or fusing of plastics (Dunn et al. 2018; Stefaniak et al. 2018; 2019a; 2019b); (3) coating utensils and cookware with polytetrafluoroethylene; and (4) high energy or high heat processing of plastics products such as laser cutting or high-speed drilling and treatment of polymer composites (Bello et al. 2010; Walter et al. 2015). Emission rates of NMP in these processes potentially leading to worker exposure in the facilities hosting plastic processers and printers would depend on a type of polymer and process used. For example, studies of incidental NMP emissions during extrusion 3D printing showed that emission rates depend strongly on filament material with polylactic acid (PLA) filaments producing less NMP than acrylonitrile butadiene styrene (ABS) filaments (Azimi et al. 2016).

There are other types of 3D printing, including multi-jet fusion and powder bed fusion, which utilize manufactured NMP (most commonly nylon powder). In facilities housing such printers, workers could be exposed to manufactured NMP as well as incidental NMP from uncontrolled process emissions. High concentrations of dust (9.1 mg/m^3 and 2.4 mg/m^3 for powder bed and multi-jet fusion processes, respectively) were reported for post-processing of manufactured products, while during manufacturing dust concentrations were low for both types of 3D printing (less than 0.4 mg/m^3) (Väisänen et al. 2019).

Despite examples of exposure to selected NMP such as flocking particles, there is practically no literature on inhalation exposure of workers to the ubiquitous NMP that are in all environmental compartments. Exact mechanisms of generation of such NMP from industrial sources require further studies. Until these gaps in knowledge are addressed, any concern about risk that workers may face from NMP remains speculative.

Potential hazards of nano- and microplastics

Toxicity of inhaled NMP is not well characterized in part due to the complexity of their chemical compositions and size and shape distributions and due to common association with other chemical hazards producing mixed exposures (Lim et al. 2021). It has been shown *in vivo* that inhalation of a pristine form of NMP can elicit an inflammatory response (Lim et al. 2021). Chronic inflammation following particulate matter exposure can lead to lung diseases including cancer through several different mechanisms including dust overload, oxidative stress, and cytotoxicity, as reviewed by Prata (2018). Inflammation could be compounded by the adverse biological response to chemicals and metals also present on the surface of the particles (the “Trojan horse” mechanism [Limbach et al. 2007]). For example, an *in vitro* toxicity study of PVC particles produced in different formulations indicates that at least some of the observed cytotoxicity was due to the additives such as surfactants present in these particles (Xu et al. 2002). *In vivo* studies of extrusion 3D printer emissions using ABS filament caused minimal transient pulmonary and systemic toxicity in animal models (Farcas et al. 2020).

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

NMP cleared from the lung through mucociliary escalator can result in oral uptake of the particles and end up in the gastrointestinal tract. Animal studies suggest that ingested NMP can cause inflammation, oxidative stress, and intestinal flora disorders in intestine and oxidative stress and lipid metabolism disorders in liver (Yin et al. 2021).

Potential health hazards of environmental NMP to the general population are a subject of research and debate. At the same time, adverse health effects of occupational exposures to NMP have been known for decades (Prata 2018). For example, inhalation of thermal degradation products of polytetrafluoroethylene can lead to “polymer fume fever” (Williams et al. 1974) and in extreme cases to fatal acute pulmonary edema (Lee et al. 1997). These adverse health effects were associated with the presence of nanoscale particles comprised of decomposition products, including polymers, in the fumes, which can reach deep into the lung and access the pulmonary interstitium (Ferin and Oberdörster 1992). Inhalation of flocking fiber particles can lead to interstitial lung disease (Lougheed et al. 1995). Exposure to PVC dust produced during the manufacture of this plastic was reported to result in the loss of lung function (Soutar et al. 1980). A review of adverse health effects among workers resulting from occupational exposures to microplastics identified three industries with potential chronic high-level exposures to airborne microplastics: the synthetic textile industry, the flock industry, and vinyl chloride and PVC industry (Prata 2018).

Exposure mitigation for nano- and microplastics

The U.S. National Institute for Occupational Safety and Health (NIOSH) has been studying workplace particles suspended in the air (aerosols), since it was created in 1970. In those five decades, NIOSH helped with establishing methods to characterize aerosols including particle size and shape distribution, concentration, and chemical composition and to minimize exposure to them. In the last decade, the NIOSH Nanotechnology Research Center (NTRC) (NIOSH 2021b) developed approaches for exposure measurement, assessment and mitigation, and hazard characterization for engineered nanomaterials. Many of the approaches would also be applicable to characterize and minimize risk of NMP in the workplace. For example, the NIOSH NTRC demonstrated that existing exposure mitigation techniques such as local exhaust ventilation and High Efficiency Particulate Air (HEPA) filters effectively reduce concentration of airborne particles including those in the nanoscale (NIOSH 2013).

Accumulating exposure and hazard data for NMP can create opportunities for the application of the Prevention-through-Design/Safe-by-Design approaches (NIOSH 2021c) by minimizing emissions and exposures to NMP in the workplace and by substituting NMP with less hazardous materials. For example, it has been shown that the use of polymer filaments requiring lower temperatures in extrusion 3D printing significantly reduces emission levels (Azimi et al. 2016). Engineering controls for capturing emissions directly at the extruder head can be incorporated into 3D printer designs, leading to lower exposure potential for workers (Dunn et al. 2020).

Although several of the chemicals that are used to synthesize plastics have occupational exposure limits, there are none that exist for specific NMP particulates. There is also

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

little information on bioaccumulation or bioavailability of these components and/or the particles themselves and toxicity that may result limiting our ability to use chemical-specific occupational exposure limits. Thus, NMP particulates would be regulated under the Permissible Exposure Limit for inert or nuisance dust set at 5 mg/m^3 for the respirable fraction (OSHA 2021). [For comparison, NIOSH Recommended Exposure Limit for nanoscale titanium dioxide is set at 0.3 mg/m^3 (NIOSH 2011)]. In the absence of occupational exposure limits specific to nano- and microplastics workplace safety efforts should focus on minimizing potential exposure through appropriate engineering controls such as isolation cabinets, exhaust ventilation, and utilizing good industrial hygiene practices (Dunn et al. 2018). For example, in 2020, NIOSH published a good practice document for the use of extrusion 3D printers in the workplace entitled “3D Printing with Filaments: Health and Safety Questions to Ask,” which cites health and safety questions with different control options and information to reduce exposure to potential hazards (NIOSH 2020). It draws attention to possible hazards and suggests controls for all printing stages. For example, it recommends choosing PLA filament rather than ABS when possible and using HEPA-filtered local exhaust ventilation placed near printing to minimize potential exposures (NIOSH 2020). On-going toxicity and exposure studies of 3D printer emissions could lead to accumulation of enough data to develop occupational exposure limits for their emission products.

Ongoing work

U.S. government agencies coordinate their work on all aspects of NMP through an informal interest group under the interagency Nanoscale Science, Engineering, and Technology subcommittee (NNI 2021). In addition, the Save Our Seas 2.0 Act (P.L. 116–224) established the Interagency Marine Debris Coordinating Committee with a focus on NMP in the marine environment in 2020 (116th Congress 2020). This law authorized additional funds for the National Institute of Standards and Technology (NIST) to develop measurement techniques for characterizing NMP in marine debris (NIST 2021) and for the Environmental Protection Agency (EPA) to award grants aiming to remove NMP from drinking water or sources of drinking water. Among other agencies active in the NMP area, the Food and Drug Administration (FDA) is focusing on the safety of NMP in food (Patri 2020). The National Science Foundation (NSF) funded proposals looking at broad impacts of NMP on the environment (NSF 2020). The Consumer Product Safety Commission (CPSC) collaborated with other agencies including NIOSH to study emissions of NMP during 3D printing (CPSC 2020). While most of these efforts are not directly aimed at workplace safety, some newly developed measurement techniques and toxicity data could be relevant for workplace exposures to NMP. NIOSH, as the sole U.S. federal government agency charged with conducting research to protect workers’ health, continues to be engaged with its public and private sector partners to better understand specific industrial applications or processes where there is a potential for exposure to NMP in the workplace, their hazards, and tools to minimize exposures.

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

References

116th Congress. 2020. Save Our Seas 2.0 Act. Public Law 116-224-Dec. 18, 2020. Washington (DC): Government Printing Office; [accessed 2021 July 15]. https://www.congress.gov/116/plaws/publ224/PLAW-116publ224.pdf.

Alexy P, Anklam E, Emans T, Furfari A, Galgani F, Hanke G, Koelmans A, Pant R, Saveyn H, Kluettgen BS. 2020. Managing the analytical challenges related to micro- and nanoplastics in the environment and food: filling the knowledge gaps. Food Addit Contam Part A Chem Anal Control Expo Risk Assess. 37(1):1–10. doi:10.1080/19440049.2019.1673905

Allan J, Belz S, Hoeveler A, Hugas M, Okuda H, Patri A, Rauscher H, Silva P, Slikker W, Sokull-Kluettgen B, et al. 2021. Regulatory landscape of nanotechnology and nanoplastics from a global perspective. Regul Toxicol Pharmacol. 122:104885. doi:10.1016/j.yrtph.2021.104885 [PubMed: 33617940]

Azimi P, Zhao D, Pouzet C, Crain NE, Stephens B. 2016. Emissions of ultrafine particles and volatile organic compounds from commercially available desktop three-dimensional printers with multiple filaments. Environ Sci Technol. 50(3):1260–1268. doi:10.1021/acs.est.5b04983 [PubMed: 26741485]

Bello D, Wardle BL, Zhang J, Yamamoto N, Santeufemio C, Hallock M, Virji MA. 2010. Characterization of exposures to nanoscale particles and fibers during solid core drilling of hybrid carbon nanotube advanced composites. Int. J. Occup. Environ. Health 16(4):434–450. doi:10.1179/oeh.2010.16.4.434 [PubMed: 21222387]

Burkhart J, Piacitelli C, Schwegler-Berry D, Jones W. 1999. Environmental study of nylon flocking process. J Tox Env Health Part A. 57:1–23.

Castelvetro V, Corti A, Biale G, Ceccarini A, Degano I, La Nasa J, Lomonaco T, Manariti A, Manco E, Modugno F, et al. 2021. New methodologies for the detection, identification, and quantification of microplastics and their environmental degradation by-product. Environ Sci Pollut Res. 28:46764–46780. doi:10.1007/s11356-021-12466-z.

Consumer Product Safety Commission (CPSC). 2020. Safety concerns associated with 3D printing and 3D printed consumer products. Bethesda (MD): U.S. Consumer Product Safety Commission; [accessed 2021 July 15]. https://www.cpsc.gov/s3fs-public/Safety-Concerns-Associiated-with-3D-Printing-and-3D-Printed-Consumer-Products.pdf.

Ding Y, Wohlleben W, Boland M, Vilsmeier K, Riediker M. 2017. Nano-object release during machining of polymer-based nanocomposites depends on process factors and the type of nanofiller. Ann Work Expo Health. 61(9): 1132–1144. doi:10.1093/annweh/wxx081 [PubMed: 29136418]

Dris R, Gasperi J, Mirande C, Mandin C, Guerrouache M, Langlois V, Tassin B. 2017. A first overview of textile fibers, including microplastics, in indoor and outdoor environments. Environ Pollut. 221:453–458. doi:10.1016/jenvpol.2016.12.013 [PubMed: 27989388]

Dunn KL, Hammond D, Menchaca K, Roth G, Dunn KH. 2020. Reducing ultrafine particulate emission from multiple 3D printers in an office environment using a prototype engineering control. J Nanopart Res. 22:112.

Dunn KL, Hammond D, Tyrawski J, Duling MG. 2018. Characterizing 3D printing emissions and controls in an office environment. NIOSH Science Blog. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; [accessed 2021 June 25]. https://blogs.cdc.gov/niosh-science-blog/2018/08/16/3d-printing/.

Farcas MT, McKinney W, Qi C, Mandler KW, Battelli L, Friend SA, Stefaniak AB, Jackson M, Orandle M, Winn A, et al. 2020. Pulmonary and systemic toxicity in rats following inhalation exposure of 3-D printer emissions from acrylonitrile butadiene styrene (ABS) filament. Inhal Toxicol. 32(11–12):403–418. doi:10.1080/08958378.2020.1834034 [PubMed: 33076715]

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

Ferin J, Oberdörster G. 1992. Polymer degradation and ultrafine particles: potential inhalation hazards for astronauts. Acta Astronaut. 27:257–259. doi:10.1016/0094-5765(92)90206-x [PubMed: 11537570]

Gigault J, ter Halle A, Baudrimont M, Pascal P-Y, Gauffre F, Phi T-L, Hadri HE, Grassl B, Reynaud S. 2018. Current opinion: what is a nanoplastic? Environ Pollut. 235:1030–1034. doi:10.1016/j.envpol.2018.01.024 [PubMed: 29370948]

Han J, He S. 2021. Need for assessing the inhalation of micro(nano)plastic debris shed from masks, respirators, and home-made face coverings during the COVID-19 pandemic. Environ Pollut. 268(Pt B):115728–115732. doi: 10.1016/j.envpol.2020.115728 [PubMed: 33065479]

Hantoko D, Li X, Pariatamby A, Yoshikawa K, Horttanainen M, Yan M. 2021. Challenges and practices on waste management and disposal during COVID-19 pandemic. J Environ Manage. 286:112140. doi:10.1016/j.jenvman.2021.112140 [PubMed: 33652254]

Huaux F 2018. Emerging role of immunosuppression in diseases induced by macro- and nano-particles: time to revisit the exclusive inflammatory scenario. Front Immunol. 9:2364. [PubMed: 30510551]

International Organization for Standardization (ISO). 2020. Plastics—environmental aspects—state of knowledge and methodologies. Geneva (Switzerland): ISO (ISO/TR 21960:2020).

Kang J, Erdely A, Afshari A, Casuccio G, Bunker K, Lersch T, Dahm MM, Farcas D, Cena L. 2017. Generation and characterization of aerosols released from sanding composite nanomaterials containing carbon nanotubes. NanoImpact. 5:41–50. doi:10.1016/j.impact.2016.12.006

Lau WWY, Shiran Y, Bailey RM, Cook E, Stuchtey MR, Koskella J, Velis CA, Godfrey L, Boucher J, Murphy MB, et al. 2020. Evaluating scenarios toward zero plastic pollution. Science 369:1455–1461. [PubMed: 32703909]

Lee EG, Cena L, Kwon J, Afshari A, Park H, Casuccio G, Bunker K, Lersch T, Gall A, Pham H, Wagner A, Agarwal S, Dinu CZ, Gupta R, Friend SA, Stueckle TA. 2020. Characterization of aerosolized particles from nano-clay-enabled composites during manipulation processes. Env. Sci. Nano 7(5):1539–1553.

Lee CH, Guo YL, Tsai PJ, Chang HY, Chen CR, Chen CW, Hsiue TR. 1997. Fatal acute pulmonary oedema after inhalation of fumes from polytetrafluoroethylene (PTFE). Eur Respir J. 10(6):1408–1411. doi:10.1183/09031936.97.10061408 [PubMed: 9192951]

Lim D, Jeong J, Song KS, Sung JH, Oh SM, Choi J. 2021. Inhalation toxicity of polystyrene micro(nano)plastics using modified OECD TG 412. Chemosphere. 262: 128330. doi:10.1016/j.chemosphere.2020.128330 [PubMed: 33182093]

Lim XZ. 2021. Microplastics are everywhere—but are they harmful? Nature. 593(7857):22–25. doi:10.1038/d41586-021-01143-3 [PubMed: 33947993]

Limbach LK, Wick P, Manser P, Grass RN, Bruinink A, Stark WJ. 2007. Exposure of engineered nanoparticles to human lung epithelial cells: influence of chemical composition and catalytic activity on oxidative stress. Environ Sci Technol. 41(11):4158–4163. doi:10.1021/es062629t [PubMed: 17612205]

Lougheed MD, Roos JO, Waddell WR, Munt PW. 1995. Desquamative interstitial pneumonitis and diffuse alveolar damage in textile workers. Potential role of mycotoxinsChest. 108(5):1196–1200. doi:10.1378/chest108.5.1196

Mitrano D 2019. Nanoplastic should be better understood. Nat Nanotech. 14:299.

National Institute for Occupational Safety and Health (NIOSH). 2011. Current intelligence bulletin 63: occupational exposure to titanium dioxide. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. [DHHS (NIOSH) Publication No. 2011–160].

National Institute for Occupational Safety and Health (NIOSH). 2013. Current strategies for engineering controls in nanomaterial production and downstream handling processes. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. [DHHS (NIOSH) Publication No. 2014–102].

National Institute for Occupational Safety and Health (NIOSH). 2020. 3D printing with filaments: health and safety questions to ask. Glassford E, Dunn KL, Dunn KH, Hammond D, Tyrawski J,

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

editors. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. [DHHS (NIOSH) Publication No. 2020–115].

National Institute for Occupational Safety and Health (NIOSH). 2021a. Exposome and exposomics. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; [accessed 2021 Jun 1]. https://www.cdc.gov/niosh/topics/exposome/default.html.

National Institute for Occupational Safety and Health (NIOSH). 2021b. Nanotechnology research center. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; [accessed 2021 Jun 1]. https://www.cdc.gov/niosh/programs/nano/default.html.

National Institute for Occupational Safety and Health (NIOSH). 2021c. Prevention through Design. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; [accessed 2021 Jun 1]. https://www.cdc.gov/niosh/topics/ptd/default.html.

National Institute of Standards and Technology (NIST). 2021. Plastic pollution measurement science. Gaithersburg (MD): U.S. Department of Commerce, National Institute of Standards and Technology; [accessed 2021 Jul 15]. https://www.nist.gov/programs-projects/plastic-pollution-measurement-science.

National Nanotechnology Initiative (NNI). 2021. The NSET subcommittee. Washington (DC): The White House, Office of Science and Technology Policy; [accessed 2021 Jul 15]. https://www.nano.gov/nset.

National Science Foundation (NSF). 2020. Dear Colleague letter: critical aspects of sustainability (CAS): micro- and nanoplastics (MNP). Alexandria (VA): National Science Foundation. (NSF 20–050, March 3, 2020) [accessed 2021 Jul 15]. https://www.nsf.gov/pubs/2020/nsf20050/nsf20050.jsp.

Occupational Safety and Health Administration (OSHA). 2021. Permissible exposure limits—annotated tables. Table Z-3. Washington (DC): U.S. Department of Labor, Occupational Safety and Health Administration; [accessed 2021 Aug 24]. https://www.osha.gov/annotated-pels/table-z-3.

Patri AK. 2020. Understanding human exposure to nanoplastics/microplastics: novel agents bring novel challenges. Paper presented at: the 21 February 2020 NTP Board of Scientific Counselors Meeting; Research Triangle, NC; [accessed 2021 Jul 15]. https://ntp.niehs.nih.gov/ntp/about_ntp/bsc/2020/february/presentations/04patri_bsc_508.pdf.

Prata JC. 2018. Airborne microplastics: consequences to human health? Environ Pollut. 234:115–126. doi:10.1016/j.envpol.2017.11.043 [PubMed: 29172041]

Shin N, Drapcho J, Aich N, Guha U, Tsai CS-J. 2020. Quantification and characterization of nanometer-sized particles released from dental composite products using a multimodal approach. J. Nanopart. Res 22:345.

Soutar CA, Copland LH, Thornley PE, Hurley JF, Ottery J, Adams WG, Bennett B. 1980. Epidemiological study of respiratory disease in workers exposed to polyvinylchloride dust. Thorax. 35(9):644–652. doi:10.1136/thx.35.9.644 [PubMed: 7444838]

Starost K, Njuguna J. 2014. A review on the effect of mechanical drilling on polymer nanocomposites. IOP Conf Ser Mater Sci Eng. 64(1):012031. doi:10.1088/1757-899X/64/1/012031

Stefaniak AB, Bowers LN, Knepp AK, Luxton TP, Peloquin DM, Baumann EJ, Ham JE, Wells JR, Johnson AR, LeBouf RF, et al. 2019b. Particle and vapor emissions from vat polymerization desktop-scale 3-dimensional printers. J. Occ. Env. Hyg 16(8):519–531. doi:10.1080/15459624.2019.1612068

Stefaniak AB, Bowers LN, Knepp AK, Virji MA, Birch EM, Ham JE, Wells JR, Qi C, Schwegler-Berry D, Friend S, Johnson AR, et al. 2018. Three-dimensional printing with nano-enabled filaments releases polymer particles containing carbon nanotubes into air. Indoor Air. 28(6): 840–851. doi:10.1111/ina.12499 [PubMed: 30101413]

Stefaniak AB, Johnson AR, Du Preez S, Hammon DR, Wells JR, Ham JE, LeBouf RF, Martin SB, Duling MG, Bowers LN, et al. 2019a. Insights into emissions and exposures from use of

Author Manuscript Author Manuscript Author Manuscript Author Manuscript

industrial-scale additive manufacturing machines. Saf Health Work. 10(2): 229–236. doi:10.1016/j.shaw.2018.10.003 [PubMed: 31297287]

Väisänen AJK, Hyttinen M, Ylönen S, Alonen L. 2019. Occupational exposure to gaseous and particulate contaminants originating from additive manufacturing of liquid, powdered, and filament plastic materials and related postprocesses. J Occup Environ Hyg. 16(3): 258–271. doi:10.1080/15459624.2018.1557784 [PubMed: 30540539]

Velimirovic M, Tirez K, Verstraelen S, Frijns E, Remy S, Koppen G, Rotander A, Bolea-Fernandez E, Vanhaecke F. 2021. Mass spectrometry as a powerful analytical tool for the characterization of indoor airborne microplastics and nanoplastics. J Anal At Spectrom. 36(4):695–705. doi: 10.1039/D1JA00036E

Walter J, Hennigs C, Huse M, Hustedt M, Kaierle S, Overmeyer L. 2015. Analysis of potentially hazardous substances emitted during laser processing of carbon fiber reinforced plastics. Paper presented at: the 2015 Lasers in Manufacturing Conference; Hannover, Germany. [accessed 2021 Jun 1]. https://www.wlt.de/lim/Proceedings2015/Stick/PDF/Contribution147_final.pdf.

Williams N, Atkinson WG, Patchefsky AS. 1974. Polymer fume fever: not so benign. J Occup Med. 16:519–522. [PubMed: 4843400]

Wohlleben W, Meier MW, Vogel S, Landsiedel R, Cox G, Hirth S, Tomović Ž. 2013. Elastic CNT-polyurethane nanocomposite: synthesis, performance and assessment of fragments released during use. Nanoscale. 5(1):369–380. doi:10.1039/c2nr32711b [PubMed: 23172121]

Xu H, Hoet PHM, Nemery B. 2002. In vitro toxicity assessment of polyvinyl chloride particles and comparison of six cellular systems. J Toxicol Environ Health Part A. 65(16):1141–1159. doi:10.1080/152873902760125372

Yang L, Zhang Y, Kang S, Wang Z, Wu C. 2021. Microplastics in soil: a review on methods, occurrence, sources, and potential risk. Sci Total Environ. 780: 146546. doi:10.1016/j.scitotenv.2021.146546 [PubMed: 33770602]

Yin K, Wang Y, Zhao H, Wang D, Guo M, Mu M, Liu Y, Nie X, Li B, Li J, et al. 2021. A comparative review of microplastics and nanoplastics: toxicity hazards on digestive, reproductive and nervous system. Sci Total Environ. 774:145758. doi:10.1016/j.scitotenv.2021.145758

Zimmer AT, Maynard AD. 2002. Investigation of the Aerosols Produced by a High-speed hand-held grinder using various substrates. Ann Occup Hyg. 46:663–672. [PubMed: 12406860]