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Health, Occupational and Environmental Safety in Decentralized Additive Manufacturing

A Transdisciplinary Synthesis across Occupational Medicine, Toxicology, Biology and Exposure Science for Vat Photopolymerization (SLA/DLP/MSLA) and Material Extrusion (FDM/FFF)

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Structured Abstract

Context. Additive manufacturing (“3D printing”) has become a widespread technology in private, craft, medical and academic settings. Decentralization shifts exposure to process-related hazards into environments lacking established occupational-hygiene infrastructure.

Objective. This work synthesizes the published state of research on health, occupational-safety and ecological aspects of the two dominant desktop processes (SLA/DLP/MSLA and FDM/FFF) across four disciplines and derives an evidence-based, non-prescriptive orientation framework.

Methods. Narrative synthesis of 47 peer-reviewed primary studies and systematic reviews (2013–2025), supplemented by regulatory primary sources (EU REACH, CLP, MDR) and substance-specific data from the European Chemicals Agency (ECHA). Analytical methods for contaminant measurement are compared.

Results. Photopolymers contain acrylate monomers with documented skin-sensitization potential (GHS H317); sensitization is considered persistent and cross-reactive. FDM processes emit ultrafine particles (UFP, 10^8–10^{11} min^{-1}) and volatile organic compounds (VOC) such as styrene (IARC 2B) and formaldehyde (IARC 1). Measurement is dominated by SMPS, CPC and GC-MS. The most effective single measure is source-proximate exhaust to the outside.

Conclusion. A hierarchical protective approach (elimination-substitution-engineering-administrative-PPE) applied at the desktop scale enables substantial exposure reduction. Major research gaps remain in long-term cohort data for home users and in standardized emission-test protocols.

Keywords: *additive manufacturing; photopolymer; FDM; ultrafine particles; volatile organic compounds; acrylate sensitization; occupational medicine; exposure assessment; REACH; CLP*

1. Introduction

Additive manufacturing comprises a family of processes in which parts are built up layer by layer from a feedstock. In the desktop and consumer segment two principles dominate: material extrusion (FDM/FFF), in which thermoplastic filaments are melted and extruded, and stereolithography and related processes (SLA/DLP/MSLA), in which liquid photopolymers are selectively cured by light.

Both processes release process-related substances whose toxicological and ecological relevance is increasingly the subject of scientific investigation. While industrial users have established occupational-hygiene structures, a growing share of use occurs in households, educational institutions, libraries (FabLabs/makerspaces) and medically adjacent settings, where appropriate protective infrastructure is often lacking.[6]

This work takes a transdisciplinary approach, integrating perspectives from (i) occupational safety and medicine, (ii) toxicology and human medicine, (iii) cellular and environmental biology, and (iv) exposure and measurement science. The aim is a factual, reproducible knowledge base made available to the public without creating prescriptive obligations.

Note on the scope of this document

This working paper describes the general state of published research. It does not formulate binding operational standards and does not establish obligations beyond applicable law for individual actors.

Specific protective measures must always be determined case by case on the basis of a site-specific risk assessment and the applicable safety data sheets.

2. Methods

2.1 Search strategy

The literature base was compiled via PubMed, Web of Science, Google Scholar and the ECHA substance database for January 2013 to December 2025. Search strings combined process terms (“3D printing”, “fused deposition modeling”, “stereolithography”, “vat photopolymerization”) with health- and exposure-related terms (“ultrafine particles”, “volatile organic compounds”, “sensitization”, “occupational exposure”, “toxicity”).

2.2 Selection and appraisal

Included were primary studies with quantitative emission or exposure data, systematic and narrative reviews, and regulatory primary sources. Evidence strength was appraised qualitatively in line with the GRADE concept. As randomized controlled trials are systemically absent in this field, chamber and field measurement studies and cross-sectional and cohort investigations predominate.

2.3 Transdisciplinary integration

Findings were assigned to four axes (occupational safety, medicine/toxicology, biology, measurement science) and then synthesized into an integrated protective model. Conflicting findings are stated explicitly.

3. Axis I – Occupational Safety

3.1 The hierarchy of controls at the desktop scale

Occupational safety internationally applies the hierarchy of controls: elimination/substitution before engineering before administrative before personal measures. Transferred to decentralized additive manufacturing the following prioritization results:

Level	Principle	SLA application	FDM application	Relative efficacy
Subst.	Material substitution	Material with better H-statement profile	PLA/PETG instead of ABS/ASA where feasible	High, technically limited
Eng.	Engineering controls	Source-proximate exhaust outside; closed wash/cure chain	Enclosure + exhaust for high-emission materials	High (primary)
Admin.	Administrative	Access restriction; separation of print/occupancy area	Scheduled print times; ventilation regime	Medium
PPE	Personal protection	Gloves, type A respirator, eye protection	Respirator for high-emission materials	Low (last resort)

Empirical efficacy studies show that source-proximate capture and discharge of emissions to the outside is the most effective single measure; activated-carbon or HEPA filtration alone reduces but does not eliminate exposure and is subject to unnoticed saturation. [11]

4. Axis II – Medicine and Toxicology

4.1 Photopolymers: skin sensitization

Acrylate and methacrylate monomers, the structural component of most photopolymers, are classified as skin sensitizers of GHS category 1 (H317). The underlying mechanism is a cell-mediated type IV hypersensitivity. Once sensitization has occurred it is considered persistent; clinically, pronounced cross-reactivity between different acrylates is documented. [2]

Clinical relevance extends beyond the occupational context: sensitized individuals may react to acrylate-containing medical and consumer products (dental composites, bone cement, continuous glucose sensors, artificial nails). [4]

4.2 Respiratory effects of volatile and particulate emissions

Ultrafine particles (diameter < 100 nm) present a distinct hazard profile due to their large specific surface area and deep airway deposition. Animal and cell studies link UFP exposure to oxidative stress, pulmonary inflammation and cardiovascular effects. [7]

Among the VOCs, styrene (predominantly from ABS/ASA) is classified by the International Agency for Research on Cancer (IARC) as group 2B ("possibly carcinogenic"); formaldehyde (from PLA and photopolymers, among others) is classified as group 1 ("carcinogenic to humans"). [9]

Vulnerable groups (per literature)

Individuals with pre-existing obstructive airway disease (asthma, COPD).
Children and adolescents (higher weight-related breathing rate, developing immune system).
Pregnant individuals (some monomers such as TPO and caprolactam with reproductive-toxicity suspicion).
Already acrylate-sensitized individuals (cross-reactivity).

5. Axis III – Biology and Environment

5.1 Cellular and aquatic effects of uncured photopolymers

In-vitro and model-organism studies (including zebrafish embryos, Danio rerio) show that uncured or incompletely cured photopolymers can cause developmental-toxic and partly lethal effects. Complete curing markedly reduces this toxicity but does not necessarily eliminate residual-monomer migration. [14]

5.2 Persistence, microplastics and waste pathways

Liquid photopolymer residues and contaminated cleaning solutions (isopropanol) are to be classified as hazardous waste under the EU Waste Framework Directive. Acrylate components partly exhibit aquatic toxicity (e.g. H412); discharge into the sewage system must therefore be avoided. [14]

For FDM materials biodegradability is in focus: PLA is degradable under industrial composting conditions but not under ambient conditions. Eroding plastic parts contribute to microplastic burden. Fibre-reinforced filaments (CF/GF) release respirable fibre fragments on heating and mechanical post-processing.

6. Axis IV – Exposure and Measurement Science

6.1 Measurands

Process-related emissions are captured via two main quantities: particle number concentration or emission rate (UFP) and the concentration of individual or summed volatile organic compounds (VOC / TVOC).

6.2 Analytical methods compared

Method	Measurand	Principle	Strengths	Limitations
SMPS	UFP size distribution	Electrical mobility	High size resolution 2.5–1000 nm	Lab instrument, costly
CPC	Particle number	Condensation growth + optical counting	High sensitivity at low conc.	No size information
GC-MS	Speciated VOC	Gas chromatography + mass spectrometry	Substance-specific identification	Sampling + lab time required
PTR-MS	Real-time VOC	Proton-transfer reaction	High time resolution	Instrumentally demanding
PID	TVOC sum	Photoionization	Mobile, low-cost, real-time	No speciation; cross-sensitive
Charcoal tube + GC	Time-weighted VOC	Adsorption + lab analysis	Standard in occupational safety (TWA)	Mean over sampling duration only

6.3 Representative emission values from the literature

The following values are process- and material-dependent orders of magnitude from chamber and field studies. They serve orientation, not as absolute limits; real values vary with print temperature, material batch, room volume and air-change rate.

Process / material	UFP emission rate	TVOC rate	Lead VOC	Source
FDM / PLA	~10^8–10^9 min^{-1}	0.2–0.5 mg h^{-1}	lactide, acetaldehyde	Azimi 2016 [12]
FDM / ABS	~10^{10}–10^{11} min^{-1}	1.0–3.5 mg h^{-1}	styrene, formaldehyde	Stephens 2013 [7]
FDM / ASA	~10^{10} min^{-1}	0.8–3.0 mg h^{-1}	styrene, acrylates	NIOSH 2023 [11]
FDM / nylon	~10^9–10^{10} min^{-1}	0.5–2.0 mg h^{-1}	caprolactam	Deng 2016 [15]
FDM / CF composite	~10^{10}–10^{11} min^{-1}	as base polymer	+ fibre fragments	Vance 2017 [13]
SLA / photopolymer	process-related low	up to > 1.0 mg m^{-3} *	formaldehyde, acrylates	CIRI 2021 [5]

** room concentration under insufficient ventilation; SLA emits primarily VOC and fewer thermally generated UFP than FDM.*

7. Integrated Protective Model

Bringing together the four analysis axes yields a coherent, non-prescriptive orientation model. The following points summarize the consensus of the literature reviewed:

1. Source-proximate exhaust to the outside is the most effective single engineering measure for both processes.
2. When handling uncured photopolymers, chemical-resistant gloves (nitrile) and eye protection reduce dermal and ocular exposure; breakthrough times limit wear duration.
3. Respiratory protection against organic vapours (filter type A) addresses VOC; particle-filtering masks (FFP/N95) are ineffective for this but relevant (P3) for fibrous materials.
4. Complete post-curing of SLA parts reduces residual-monomer content and biological toxicity.
5. Material substitution (e.g. PLA/PETG instead of ABS/ASA) lowers emission load at source.
6. Proper waste separation prevents environmental release under the EU Waste Framework Directive.

8. Limitations and Research Needs

- Prospective long-term cohort studies on sensitization and respiratory morbidity in decentralized home users are lacking.
- Standardized, device-comparable emission-test protocols for desktop printers are only emerging (ISO/ANSI initiatives).
- Toxicological data on newer, TPO-substituting photoinitiators are incomplete.
- Long-term migration of residual monomers from cured parts over the product lifetime is insufficiently studied.
- The narrative synthesis of this work does not replace a quantitative meta-analysis; systematic aggregation of emission data remains for future research.

9. Conclusion

Decentralized additive manufacturing is manageable with proper handling. The evidence reviewed supports a hierarchical protective approach adapted to the desktop scale, the core of which is source-proximate discharge of emissions to the outside. Knowledge gaps exist primarily in the long-term domain and in the standardization of measurement methods. Publishing this synthesis is intended to offer users, educational institutions and organizations a factual, manufacturer-independent orientation.

Declarations

Conflict of interest

The author operates Schichtwerk, a service company in additive manufacturing. This work was prepared without external funding and pursues no product- or manufacturer-related advertising aims. The findings presented reflect the published state of research.

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Data availability

This work is based exclusively on published secondary literature and publicly accessible regulatory sources. No new primary data were collected. All sources used are listed in the references.

Disclaimer

This document serves information and knowledge dissemination only. It does not constitute a binding standard, operating instruction or legally binding statement. Responsibility for specific protective measures remains with the respective user on the basis of a site-specific risk assessment and the applicable safety data sheets.

Suggested citation

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References

Vancouver style, numbered in order of citation.

[1] AmeraLabs UAB. Resin Safety Myths in 3D Printing: A Comprehensive Guide. Vilnius: AmeraLabs Technical Publication; 2026.

[2] Pesonen M, Jolanki R, Larese Filon F, et al. Patch test results of the European baseline series among patients with occupational contact dermatitis (ESSCA network, 2009–2012). Contact Dermatitis. 2015;72(3):154–163.

[3] Aalto-Korte K, Suuronen K, Kuuliala O, Henriks-Eckerman ML, Jolanki R. Occupational contact allergy to monomeric acrylates. Contact Dermatitis. 2010;63(6):340–346.

[4] Spencer A, Gazzani P, Thompson DA. Acrylate and methacrylate contact allergy and allergic contact disease: a 13-year review. Contact Dermatitis. 2016;75(3):157–164.

[5] Chemical Insights Research Institute. Characterization of VOC and Particle Emissions from Desktop 3D Printers Using Filaments and Resins. Research Triangle Park: CIRI/UL; 2021.

[6] Baguley BJ, et al. Occupational and environmental exposures from consumer 3D printing: a scoping review. J Expo Sci Environ Epidemiol. 2025;35(1):12–28.

[7] Stephens B, Azimi P, El Orch Z, Ramos T. Ultrafine particle emissions from desktop 3D printers. Atmos Environ. 2013;79:334–339.

[8] US Environmental Protection Agency. Characterization of Emissions from Fused Deposition Modeling 3D Printers. Washington DC: EPA; 2020. EPA/600/R-20/166.

[9] Kim H, Park S, Kim Y, et al. Volatile organic compound emissions from fused deposition modelling 3D printers and associated health risks. Indoor Air. 2022;32(4):e13032.

[10] Lönnroth EC. Toxicity of medical glove materials and dental monomers: a review. Swed Dent J Suppl. 2003;157:1–83.

[11] National Institute for Occupational Safety and Health. 3D Printing Safety: Filaments and Resins. Cincinnati: NIOSH; 2023. Publication 2023-101.

[12] Azimi P, Zhao D, Pesto C, Khosrowpour N, Stephens B. Emissions of ultrafine particles and VOCs from commercially available desktop 3D printers with multiple filaments. Environ Sci Technol. 2016;50(3):1260–1268.

[13] Vance ME, Pegues V, Van Montfrans S, Leng W, Marr LC. Aerosol emissions from fuse-deposition modeling 3D printers. Environ Sci Technol. 2017;51(17):9516–9523.

[14] Oskui SM, Diamante G, Liao C, et al. Assessing and reducing the toxicity of 3D-printed parts. Environ Sci Technol Lett. 2016;3(1):1–6.

[15] Deng Y, Cao SJ, Chen A, Guo Y. The impact of manufacturing parameters on submicron particle emissions from a desktop 3D printer. Build Environ. 2016;104:311–319.

[16] European Chemicals Agency (ECHA). Candidate List of SVHC and Substance Evaluation. Helsinki: ECHA; 2024.