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Systematic review

Airborne Volatile Organic Compound and Particle Emissions from Vat-Photopolymerization 3D Printing and Mechanical Finishing in Dental Laboratories: A Systematic Review of Occupational Exposure

Badr Mohammad Alkhudhir[1], Abdulrahman Mohammed Alhamrani[2], Awadh Jamman Alhafi[3], Nasser Mohammed Al Hasenh[4]

1. Dental Technology, College of Dentistry, King Saud University, Riyadh, Saudi Arabia. Email: balkoder@ksu.edu.sa
2. Dental Technology, College of Dentistry, King Saud University, Riyadh, Saudi Arabia. Email: Amshamrani@ksu.edu.sa
3. General Dentist, Dental University Hospital, King Saud University, Riyadh, Saudi Arabia. Email: alhafi@ksu.edu.sa. ORCID: 0009-0001-1455-5491
4. Dental Technology, College of Dentistry, King Saud University, Riyadh, Saudi Arabia. Email: Nasser@ksu.edu.sa

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Abstract

Background: Dental laboratories now combine vat-photopolymerization (VP) printers with computer-aided design/computer-aided manufacturing (CAD/CAM) milling and finishing equipment, and both release airborne contaminants near the technician. Objective: To synthesize measured emissions of volatile organic compounds (VOCs) and airborne particles from VP printing and mechanical finishing, including CAD/CAM milling, in dental laboratories. Methods: Following PRISMA 2020, two authors independently searched PubMed, Scopus, and Web of Science to November 2026, screened records, and extracted data. Risk of bias was appraised with an adapted Joanna Briggs Institute checklist, and findings were synthesized narratively. Results: Thirteen studies published between 2011 and 2026 were included: nine on VP printing and four on mechanical finishing. VP printers released methacrylate monomers,

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aldehydes, and solvent vapours, with total VOC concentrations up to 36.8 mg/m³ during isopropanol washing and above 128 mg/m³ inside a closed chamber. Particle output from VP printing was low in number and mostly nanoscale. Mechanical finishing produced nanoparticle peaks of 773,000 particles/cm³ and fine particulate mass up to 1645 µg/m³ with metal content. No study measured an operating CAD/CAM milling unit. Vat lids, distance, filtered extraction, and portable air cleaners lowered concentrations by up to 97%. Risk of bias was low in five studies, moderate in five, and high in three. Conclusion: VP printing acts mainly as a VOC source and mechanical finishing as a particle source in dental laboratories. Breathing-zone data for dental technicians and standardized emission metrics are needed.

Keywords: dental laboratory; vat photopolymerization; mechanical finishing; volatile organic compounds; particulate matter; ultrafine particles; occupational exposure; indoor air quality

Introduction

Dental laboratories increasingly combine additive and subtractive digital fabrication within one workflow (1). Photopolymer resins processed by stereolithography (SLA), digital light processing (DLP), and related vat-photopolymerization (VP) methods now produce diagnostic models, surgical guides, occlusal devices, denture bases, and provisional restorations (2). Computer-aided design/computer-aided manufacturing (CAD/CAM) milling of zirconia, lithium disilicate, and polymethyl methacrylate (PMMA) blocks remains the main subtractive route, and a recent scoping review reported material waste below 5% for printing against more than 30-40% for milling (1). VP processing also involves resin pouring, solvent washing, and ultraviolet post-curing, and each step brings the operator close to uncured or partially cured resin (2).

Respiratory disease among dental technicians has a long record in the occupational literature (3). In technicians manufacturing cobalt-chromium-molybdenum constructions, 16% had radiological evidence of pneumoconiosis, and local exhaust ventilation was identified as an effective means of reducing this hazard (4). Among self-employed dental technicians in Paris aged 43-68 years, cough and phlegm lasting three weeks or more were more frequent than in controls (16.9% versus 2.9%) (3). Allergic contact dermatitis from acrylates is common in dental personnel, and acrylate preparations also caused occupational asthma, rhinitis, and laryngitis in cases diagnosed in Finland (5). Reviews of additive manufacturing report that non-metal processes release organic gases that include respiratory irritants, asthmagens such as methyl methacrylate, and carcinogens such as formaldehyde and acetaldehyde (6).

Nanoparticles, defined by a size from 1 to 100 nm, occur in many dental materials as embedded fillers or as by-products of filler milling, and the lungs represent their main target organ (7). Most emission studies on desktop printers have examined filament extrusion, and the resin printer data that exist describe mainly carbonyl compounds and methacrylate monomers (8). Published syntheses compare printing and milling on accuracy, efficiency, and waste, or describe additive manufacturing emissions across industrial settings without a dental focus (1, 6). Exposure to nanoparticles in the dental laboratory falls under occupational legal regulation (7). This systematic review synthesized measured airborne volatile organic compound (VOC) and particle emissions, including ultrafine particles (UFPs), from VP printing and mechanical finishing in dental laboratories, to identify dominant sources, phases of highest release, and the effect of control measures, in response to the research need stated for resin printers.

Methods

Protocol and search strategy

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses

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(PRISMA) 2020 statement. Two authors independently searched PubMed, Scopus, and Web of Science from inception to November 2026 and hand-searched reference lists of included studies. The PubMed string, adapted for the other databases, was: ("Printing, Three-Dimensional"[MeSH] OR "3D printing" OR "vat photopolymerization" OR stereolithography OR "digital light processing" OR "CAD/CAM" OR milling OR grinding OR polishing OR finishing) AND ("Volatile Organic Compounds"[MeSH] OR "volatile organic compound*" OR "ultrafine particle*" OR nanoparticle* OR "Particulate Matter"[MeSH] OR emission*) AND (dental OR dentistry OR resin* OR "occupational exposure").

Eligibility criteria

Eligibility followed the population, exposure, comparator, and outcome (PECO) framework. Studies were eligible when they measured airborne total VOC (TVOC), speciated VOCs, carbonyls, particle number or size, particulate matter (PM2.5, PM10), or emission rates in dental laboratories, dental schools, clinics, or test chambers during VP printing (SLA or DLP, including washing and curing) or mechanical finishing of prosthetic materials (CAD/CAM milling, grinding, trimming, or polishing), against background air, non-working periods, or alternative resins, printers, or controls. Original peer-reviewed English-language studies were included, whereas studies limited to material extrusion or powder-bed processes, intraoral restorative procedures, toxicity without emission data, reviews, and conference abstracts were excluded.

Study selection and data extraction

After duplicate removal, two authors independently screened titles, abstracts, and full texts, resolving disagreements by consensus. The search identified 788 records (PubMed, n = 255; Scopus, n = 260; Web of Science, n = 273); after removal of 201 duplicates, 587 records were screened and 562 were excluded. Of 25 full-text reports assessed, 12 were excluded (material extrusion only, n = 6; intraoral restorative composite grinding, n = 3; metal powder-bed fusion, n = 1; intraoral matting sprays, n = 1; cured-device outgassing without fabrication-phase sampling, n = 1), leaving 13 studies. The same authors extracted study characteristics, metrics, findings, and control measures into a piloted form.

Risk of bias assessment and synthesis

Two authors independently applied the Joanna Briggs Institute (JBI) checklist for analytical cross-sectional studies, adapted to emission measurement: D1, source and setting described; D2, process and material defined; D3, process conditions recorded; D4, standardized measurement conditions; D5, confounding sources identified; D6, confounding sources handled; D7, valid and reliable measurement; and D8, appropriate analysis. Domains were rated yes (Y), no (N), or unclear (U); seven or eight "yes" ratings indicated low risk, five or six moderate, and four or fewer high (Table 1). Heterogeneous metrics and designs precluded meta-analysis, so findings were synthesized narratively by process and workflow phase following the Synthesis Without Meta-analysis (SWiM) guideline.

Results

Study characteristics

Thirteen studies published between 2011 and 2026 were included, and Table 2 lists their characteristics (9-21). Nine examined VP printing, and two of these sampled printer workrooms or a ventilated facility rather than test chambers (12, 13). The remaining four measured particles from grinding, trimming, or polishing, and none sampled an operating CAD/CAM milling unit (18-21). Risk of bias was low in five studies, moderate in five, and high in three, owing to a saturated consumer-grade sensor or

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incomplete reporting of sampling conditions (17, 18, 20).

Emissions from VP printing

TVOC yields were 161-322 µg/g printed for SLA printers and 1281-1931 µg/g for DLP printers (9). Isopropanol rinsing, soaking, and drying produced TVOC concentrations up to 36.8 mg/m³, against up to 3 mg/m³ during curing and 0.1 mg/m³ during printing (10). In a standardized chamber test, SLA printing with washing and curing units reached TVOC emission rates above 4 mg/h (11). Inside an enclosed chamber, TVOC exceeded 128,000 µg/m³, whereas values at 50 cm in a ventilated room were 45-116 µg/m³ (16). Field sampling 10 cm above a resin printer recorded 22.6-1918 µg/m³ depending on the resin (13). Headspace testing of dental resins gave TVOC values of 0.69-2.29 mg/m³, and formaldehyde exceeded the 5.00 mg/m³ instrument limit for three resins (17). 2-Hydroxypropyl methacrylate and 2-hydroxyethyl methacrylate (2-HEMA) recurred among emitted compounds, together with acetaldehyde (10, 16). A built-in resin heater was linked to higher particle and 2-HEMA yields, whereas resin colour had a minor effect (15). Idle printers with uncovered vats emitted as much as or more than active printing (14). Particle yields during printing were 1.3-9.2 × 10^8 particles/g, with geometric mean (GM) diameters of 15.3-45.1 nm and an estimated 15-37% alveolar deposition (9). Cured parts continued to outgas, and total emissions fell by 84-96% after 28 days (12).

Particles from mechanical finishing

In a dental laboratory, working-period nanoparticle concentrations reached 28,000-74,000 particles/cm³, with peaks up to 773,000 particles/cm³ (19). PM2.5 in six dental prosthesis laboratories ranged from 80.8 to 1645 µg/m³ and contained beryllium, cadmium, cobalt, chromium, nickel, and mercury (20). Grinding a PMMA occlusal splint released about 25,000 particles at the source within 30 seconds, dominated by 0.3-0.5 µm sizes (21). Trimming and polishing orthodontic appliances stayed well below workplace exposure limits (WELs) under suitable ventilation, whereas the plaster hopper produced the highest respirable dust (18).

Control measures

A fabricated vat lid lowered idle-printer VOC emissions by 70-97% (14). Increasing the distance from 0.5 to 2 m, or using an extraction hood with carbon and high-efficiency particulate air (HEPA) filters, reduced TVOC by 71-84% (16). Portable air cleaners reduced simulated working-zone particle concentrations by up to 80% (21). Four-week storage of printed parts was advised to limit VOC release (12). Table 3 summarizes the findings (9-21).

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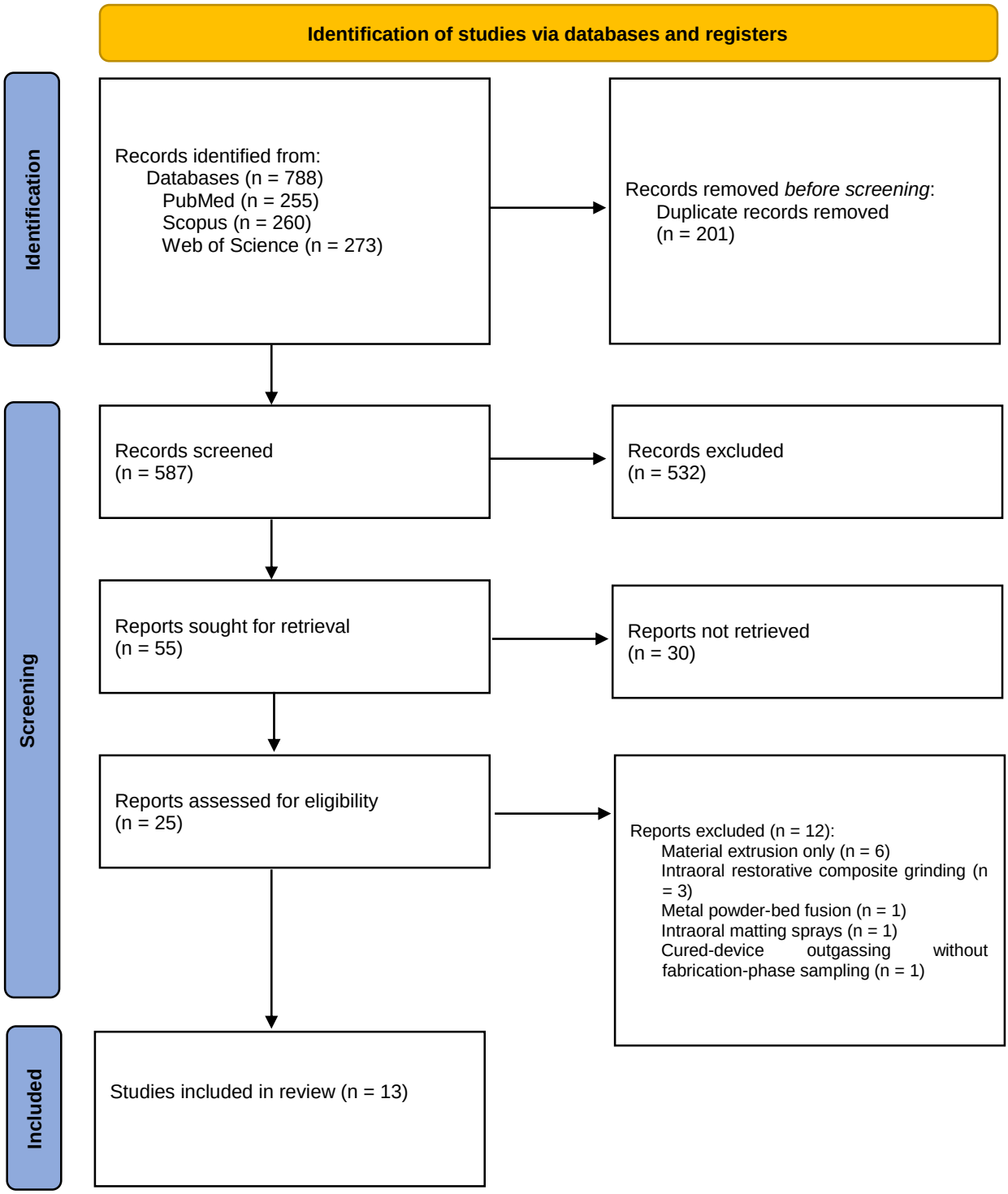

Figure 1: PRISMA flow chart

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Table 1. Risk of bias of included studies (adapted JBI checklist for analytical cross-sectional studies)

Study	D1	D2	D3	D4	D5	D6	D7	D8	Overall
Stefaniak 2019 (9)	Y	Y	Y	Y	Y	Y	Y	Y	Low
Bowers 2022 (10)	Y	Y	Y	Y	Y	U	Y	U	Moderate
Zhang 2022 (11)	Y	Y	Y	Y	Y	Y	Y	U	Low
Väisänen 2022 (12)	Y	Y	Y	U	Y	U	Y	U	Moderate
Garcia-Gonzalez 2024 (13)	Y	Y	Y	Y	Y	U	N	N	Moderate
Miller-Schulze 2025 (14)	Y	Y	Y	U	Y	Y	Y	U	Moderate
Stefaniak 2025 (15)	Y	Y	Y	Y	Y	Y	Y	Y	Low
Baguley 2026 (16)	Y	Y	Y	Y	Y	Y	Y	U	Low
Kapusta 2026 (17)	Y	Y	N	Y	U	N	N	Y	High
Ireland 2011 (18)	Y	Y	Y	U	U	U	U	U	High
Lang 2018 (19)	Y	U	Y	Y	Y	Y	Y	Y	Low
Arsal Yıldırım 2020 (20)	Y	U	Y	U	U	U	Y	Y	High
Chanbandit 2025 (21)	Y	Y	Y	Y	Y	U	N	U	Moderate

Table 2. Characteristics of included studies

Study	Design and setting	Process	Materials	Measurement
Stefaniak 2019 (9)	12.85 m^3 chamber	3 SLA and 2 DLP printers	Photopolymer resins	Particles; TVOC; carbonyls; elements
Bowers 2022 (10)	Three chambers	SLA and DLP; pouring to curing	Photopolymer resins	Particles; TVOC; specific VOCs
Zhang 2022 (11)	Standardized chamber	SLA printer; wash and cure units	SLA resin	Particle and VOC emission rates
Väisänen 2022 (12)	Workrooms; 84-day outgassing	VP and material jetting	Several resins	VOCs, carbonyls, UFPs, PM10
Garcia-Gonzalez 2024 (13)	Ventilated laboratory; companies	Resin printer; wash and cure unit	Six resins	TD-GC-MS (49 VOCs)
Miller-Schulze 2025 (14)	Laboratory; four phases	Entry-level VP printer; vat lid	Standard and Eco resins	Six target VOCs
Stefaniak 2025 (15)	Chamber	Two SLA brands	Three resin colours	Particles; TVOC; aldehydes
Baguley 2026 (16)	Chamber; room at two distances	Form 2 SLA; extraction hood	Four resins	TD-GC-MS

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Study	Design and setting	Process	Materials	Measurement
Kapusta 2026 (17)	Small chamber; liquid resin	No printing	Five dental resins	Portable monitor
Ireland 2011 (18)	Orthodontic laboratory	Plaster hopper; trimming; polishing	Gypsum; acrylic	Respirable dust
Lang 2018 (19)	Dental laboratory and office	Routine procedures	Dental materials	Mobility particle sizer; impactor
Arsal Yıldırım 2020 (20)	Six prosthesis laboratories	Smoothing; polishing	Prosthesis materials	PM2.5; ICP-MS
Chanbandit 2025 (21)	Clinic operatory; CFD	PMMA splint grinding	PMMA	Particle counter (0.3-5 µm)

Table 3. Main emission findings and control effects

Study	VOC findings	Particle findings	Controls and remarks
Stefaniak 2019 (9)	TVOC 161-322 µg/g (SLA); 1281-1931 µg/g (DLP)	1.3-9.2 × 10^8/g; GM 15.3-45.1 nm; Cr, Ni	DLP above SLA ($p < 0.05$)
Bowers 2022 (10)	TVOC ≤36.8 mg/m³ (IPA tasks); ≤3 mg/m³ (curing)	≤1200/cm³; Ba, Cr, Mn	Post-processing dominant
Zhang 2022 (11)	TVOC >4 mg/h; 45 chemicals of concern	Low	Wash and cure add VOCs
Väisänen 2022 (12)	Low operator levels	Low	Outgassing fell 84-96% by 28 days
Garcia-Gonzalez 2024 (13)	TVOC 22.6-1918 µg/m³; ethyl acetate	—	Individual VOCs <1% of OELs
Miller-Schulze 2025 (14)	Six VOCs; Standard above Eco	—	Vat lid: −70-97%
Stefaniak 2025 (15)	Brand-dependent 2-HEMA and aldehydes	Higher with resin heater	Colour minor
Baguley 2026 (16)	>128,000 µg/m³ (chamber); 45-116 µg/m³ (room)	—	Distance or hood: −71-84%
Kapusta 2026 (17)	TVOC 0.69-2.29 mg/m³; HCHO >5.00 mg/m³ (3 resins)	—	Sensor saturation
Ireland 2011 (18)	—	Plaster hopper highest	Ventilation advised
Lang 2018 (19)	—	28,000-74,000/cm³; peaks 773,000/cm³	Clusters <100 nm
Arsal Yıldırım 2020 (20)	—	PM2.5 80.8-1645 µg/m³; metals	Hazard index 187

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Study	VOC findings	Particle findings	Controls and remarks
Chanbandit 2025 (21)	—	~25,000 particles/30 s; 0.3-0.5 µm	Air cleaners: −80%

Discussion

This review found that VP printing behaved mainly as a source of VOCs, whereas mechanical finishing of prosthetic materials acted mainly as a particle source (10, 19). A field report from a university dental school showed the same pattern, with higher particle counts (1054 versus 239 particles/cm³) and PM10 (33.1 versus 1.46 µg/m³) in the grinding area and the highest TVOC in the printing area (22). Post-processing, rather than printing itself, produced the highest VOC concentrations, which directs attention to isopropanol baths and curing units (10).

Methacrylates such as 2-HEMA and hydroxypropyl methacrylates were the prominent compounds from SLA printing (16). These compounds belong to the acrylate family that caused asthma, rhinitis, and laryngitis in dental personnel (5). Among workers using 3D printers regularly, 59% reported respiratory symptoms at least once a week (23). A worker operating ten filament printers in a small room developed asthma that improved after exposure reduction (24). Individual VOC concentrations stayed far below occupational limits in field sampling (13). Many acrylates detected near SLA printers lack published exposure guidelines, which limits formal risk assessment (16). Where reference limits existed, total emissions from VP printing approached or exceeded them (14).

Particle concentrations around VP printers stayed modest (10). Their nanoscale diameters still favour deposition in the alveolar region (9). Grinding of dental composites released more than 10^6 particles/cm³ with median diameters of 38-70 nm (25). Composite dust in the 15-35 nm range entered human bronchial epithelial cells and showed cytotoxicity at the highest doses (26). The metal content of laboratory PM2.5 and the historical burden of pneumoconiosis among technicians support continued attention to finishing tasks (4, 20). Earlier assessments judged nanoparticle exposure in dentistry as low, while noting the absence of long-term data (27, 28).

Engineering controls achieved large reductions, from sealed vats and greater distance to filtered hoods and portable air cleaners (14, 16, 21). Water coolants and adequate ventilation remain the recommended controls for grinding and polishing (27). Printer selection also matters, since a built-in resin heater was linked to higher particle and methacrylate yields (15). Storing printed parts before handling limits continued outgassing (12).

The evidence base has clear limits, since most VP data came from chambers with general-purpose resins that do not reproduce multi-printer dental laboratories (9, 15, 16). The study devoted to dental resins measured liquid-resin headspace with a portable monitor that saturated for formaldehyde (17). No included study sampled an operating CAD/CAM milling unit or the breathing zone of technicians across a full digital workflow (18-21). Consolidation of 447 particle and 58 VOC evaluations for material extrusion printers shows the value of standardized emission datasets (29). Emissions from cured printed devices also reach patients, which links occupational and patient exposure (30). Like the earlier scoping review of desktop printer emissions, this review relied on narrative synthesis (8).

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Conclusion

VP printing in dental laboratories releases methacrylate monomers, aldehydes, and solvent vapours, with the highest concentrations during isopropanol washing, curing, and in poorly ventilated enclosures. Mechanical finishing of prosthetic materials generates nanoparticles and fine particulate matter containing metals. No included study measured emissions from an operating CAD/CAM milling unit. Vat lids, distance, filtered local extraction, and portable air cleaners reduce concentrations substantially, and resin selection and closed vats offer further control at the source. Dental laboratories need breathing-zone sampling of technicians across complete digital workflows, standardized emission metrics, and exposure guidance for acrylates that lack current limits.

List of abbreviations

2-HEMA, 2-hydroxyethyl methacrylate; CAD/CAM, computer-aided design/computer-aided manufacturing; CFD, computational fluid dynamics; DLP, digital light processing; GM, geometric mean; HCHO, formaldehyde; HEPA, high-efficiency particulate air; ICP-MS, inductively coupled plasma mass spectrometry; IPA, isopropyl alcohol; JBI, Joanna Briggs Institute; OEL, occupational exposure limit; PECO, population, exposure, comparator, outcome; PM2.5/PM10, particulate matter ≤2.5/≤10 µm; PMMA, polymethyl methacrylate; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; SLA, stereolithography; SWiM, Synthesis Without Meta-analysis; TD-GC-MS, thermal desorption gas chromatography-mass spectrometry; TVOC, total volatile organic compounds; UFP, ultrafine particle; VOC, volatile organic compound; VP, vat photopolymerization; WEL, workplace exposure limit.

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