Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: www.tandfonline.com/journals/uoeh20

Evaluation of chemical exposures generated from n-free nail polishes

Kimberly R. Anderson, Perri Callaway & M. Abbas Virjii

To cite this article: Kimberly R. Anderson, Perri Callaway & M. Abbas Virjii (2025) Evaluation of chemical exposures generated from n-free nail polishes, Journal of Occupational and Environmental Hygiene, 22:6, 482-494, DOI: 10.1080/15459624.2025.2468931

To link to this article: https://doi.org/10.1080/15459624.2025.2468931

Published online: 06 May 2025.

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2025, VOL. 22, NO. 6, 482–494
https://doi.org/10.1080/15459624.2025.2468931

Taylor & Francis
Taylor & Francis Group

RESEARCH ARTICLE

Evaluation of chemical exposures generated from n-free nail polishes

Kimberly R. Anderson, Perri Callaway, and M. Abbas Virjii

Field Studies Branch, Respiratory Health Division, National Institute for Occupational Safety and Health, Morgantown, West Virginia

ABSTRACT

Nail polishes contain over a dozen chemical compounds, including chemicals that can cause adverse reproductive outcomes and pose a risk to the high proportion of nail salon workers who are women of childbearing age. Consumer demand has resulted in a shift toward more natural products, with manufacturers attempting to remove harmful ingredients (n-free products). Many products that claim to have eliminated toluene, formaldehyde, and dibutyl phthalate (DBP) are labeled as "3-free"; however, studies have found these products often contain higher concentrations of toluene and DBP compared to products with no such claims. Products used only at salons are not required to list ingredients, leading to uncertainties as to the exact chemical composition and potential exposures. A better understanding of chemical exposures associated with nail polish products is necessary to understand potential worker exposures and develop effective control options. This study evaluated chemical exposures generated while painting nails with 20 n-free polishes using real-time and time-integrated air sampling. Total volatile organic compounds (TVOCs, PID, ION Science Inc.) and 22 individual compounds (FTIR, Gasmet Technologies) were measured in the breathing zone of the manicurist while two coats of polish were applied to artificial nails on a manikin in an exposure chamber and for 2 hr afterwards. Formaldehyde and toluene were measured in all polishes using the real-time FTIR, despite all claiming to be 3-free. Normalized geometric mean (GM) formaldehyde exposures from the FTIR ranged from 0.021 to 0.273 ppm/g, GM toluene exposures ranged from 0.068 to 0.534 ppm/g, and GM benzene exposures ranged from 0.076 to 0.752 ppm/g. Notably, formaldehyde, toluene, and benzene exposures did not significantly differ between different products. Neither DBP nor triphenyl phosphate (TPhP) was detected in any of the polishes. This study highlights that despite industry claims, n-free polishes may still contain chemicals associated with negative health effects and that more studies are necessary to understand the true chemical exposures of nail salon workers.

KEYWORDS
Chemical profile; exposure assessment; inhalable exposures; n-free; nail polish; nail salons

Introduction

Salons can contain hundreds of chemical compounds in the various products used during manicures, many of which are suspected or known to be associated with adverse reproductive effects, asthma, and skin and eye irritation (Quiros-Alcala et al. 2019). Potential respiratory and reproductive hazardous chemicals such as dibutyl phthalate (DBP), plasticizers, toluene, ethyl acetate, butyl acetate, and formaldehyde have been reported in nail polish products (Ceballos et al. 2021; Heaton et al. 2019; Zhong et al. 2019). In recent years, increased consumer focus on "clean" or "non-toxic" beauty products has changed product formulations, with manufacturers attempting to remove harmful ingredients. These products are labeled as "n-free," where n stands for the number of hazardous compounds removed (NPD Group 2018). The original "n-free" products, called 3-free, claimed to not contain what is known as the "toxic trio," which comprises formaldehyde (a respiratory toxicant and human carcinogen), toluene (a respiratory irritant and developmental and neurological toxicant), and DBP (an eye and respiratory irritant, reproductive and developmental toxicant); there is now a wide variety of n-free nail polishes with some claiming to be 10-free and greater (Young et al. 2018). However, there is limited research on the exposures and potential health risks associated

CONTACT Kimberly R. Anderson qdk5@cdc.gov Field Studies Branch, Respiratory Health Division, National Institute for Occupational Safety and Health, Morgantown, West Virginia.

Supplemental data for this article can be accessed online at https://doi.org/10.1080/15459624.2025.2468931. AIHA and ACGIH members may also access supplementary material at http://oeh.tandfonline.com.

with these alternative formulations, despite salons increasingly adopting green or 3-free products (Han et al. 2022; Ma et al. 2019).

The Food and Drug Administration (FDA) regulates cosmetics, but there is no standard definition for "clean" or "natural" beauty products, and nail products used only at salons are not required to list ingredients (Cosmetics FAO 2018). Furthermore, the FDA does not require specific tests to demonstrate the safety of beauty products under the Federal Food, Drug, and Cosmetic Act before marketing (Cosmetics FAO 2018). Nor is there standardization in n-free definitions or excluded chemicals, resulting in different chemical compounds being present or absent in polishes with the same n-free claim. Due to these loose regulatory constraints, uncertainties exist as to the exact chemical composition of many of these products, making it difficult to assess exposures and subsequent risk to workers. Studies testing the validity of 3-free claims over different nail products have reported higher concentrations of hazardous compounds compared to traditional products with no such claims, which raises concern about their safety (Guo et al. 2012; Young et al. 2018).

Nail salon workers are primarily exposed to chemicals through inhalation, dermal contact, and, to a lesser extent, ingestion of harmful chemicals. Chemicals found in nail products can evaporate into the air or come into direct contact with the skin during manicures or pedicures. Inhalation of vapors from these VOCs can lead to respiratory issues, headaches, dizziness, and long-term health risks like cancer or reproductive harm. Exposures to high concentrations of toluene have been associated with decreased fetal growth, premature delivery, congenital malformations, and postnatal developmental delays (Donald et al. 1991; Hannigan and Bowen 2010), as well as upper respiratory tract irritation (Cohr and Stokholm 1979). Formaldehyde is a human carcinogen, a respiratory toxicant, and may cause reproductive and developmental toxicity (Duong et al. 2011). DBT exposure is associated with birth defects, developmental delays, and adverse reproductive system effects (Han et al. 2022; Hines et al. 2009; Kwapniewski et al. 2008; Pak et al. 2011; Young et al. 2018). Furthermore, repeated skin contact with these substances may cause dermatitis or allergic reactions (Anderson and Meade 2014; de Groot and Rustemeyer 2023; DeKoven et al. 2017; Freeman et al. 1995; Hemmer et al. 1996; Kiec-Swierczynska et al. 2013; Kucharczyk et al. 2021; Semple 2004). Chronic exposure to these chemicals, especially in poorly ventilated salons, increases the risk of more severe health conditions, including neurological damage, liver toxicity, and disruptions to the endocrine system. Nail salon workers (NSWs) likely have substantially higher exposures compared to consumers due to longer exposure durations and a lack of appropriate ventilation in the workspace, and, as a result, are at much greater risk for adverse health outcomes from exposure to nail products. Many NSWs work over 30 hr a week and have been working in the field for over eight years, raising concerns about high cumulative exposures among this population (Sharma et al. 2018). Furthermore, many nail salon employees are immigrants, with 79% being foreign-born (Sharma et al. 2018). Of these employees, 46% have poor or no English proficiency (Sharma et al. 2018). Training materials and safety information are often only provided in English and may use technical terminology (Quach et al. 2013). These difficulties may lead to access issues, such as in one study, which found that 55.4% of employees felt they weren't able to access health and safety information at work (White et al. 2015). Although several studies report exposures below occupational exposure limits for individual volatile organic compounds (VOCs) (Alaves et al. 2013; Park et al. 2014; Tran et al. 2022), the effects of mixed exposures are not typically considered. Additionally, many NSWs report upper respiratory symptoms like wheezing and upper respiratory irritation (Quiros-Alcala et al. 2019); symptoms that are consistent with chronic low-level VOC exposure (Alford and Kumar 2021; Wang et al. 2014). Moreover, NSWs are mostly women (96%) and over half of NSWs are of reproductive age (54%), putting this population at a higher risk for adverse reproductive outcomes (AROs) compared to other worker populations (Sharma et al. 2018). AROs are high among NSWs, with 15.6% reported having a miscarriage, which is 4.6% above the U.S. average of 11% (Ma et al. 2019).

A better understanding of chemical exposures associated with nail polish products marketed as nontoxic alternatives is necessary to understand potential worker exposures and inform salon owners about nail product selection. The objective of this study was to evaluate airborne chemical exposures generated while painting nails with 19 n-free polishes and one standard polish with no n-free claims using real-time and time-integrated (average) air sampling.

Methods

Test chamber

This study was conducted in a 12.85 m^3 stainless steel environmental chamber with an air exchange rate of 1 air change per hour (ACH), typical of ventilation rates observed in salons, which range from 0 to ∼5.7 ACH

(Harrichandra et al. 2020; Zhong et al. 2019) while still meeting the ASTM D6670 standard practice for Full-Scale Chamber Determination of Volatile Organic Emissions from Indoor Materials/Products (Zhang et al. 2001). The chamber was assessed and fully complied with the ASTM D6670 guidelines, including a calculated mixing level of 92%, a leak rate of 0.024 ACH (assessed using SF_6), and a reversible sink ratio of less than 0.1. HEPA- and carbon-filtered air was supplied to the chamber from a 1.48 m × 0.025 m inlet spanning the back wall and was exhausted out of the chamber through a 0.133 m × 0.133 m outlet at the front of the chamber. Previous tests have determined that the exposure chamber is a well-mixed room (Stefaniak et al. 2018).

A table was set up in the center of the chamber with manikin hands positioned on one side, representing the customer, and the lab technician positioned on the other side, representing the NSW (Figure 1).

Nail products

Eleven red nail polishes (R1–R11), four top coats (TC1–TC4), and four base coats (BC1–BC4), for a total of 19 n-free nail products, were selected for evaluation. Ten unique brands were evaluated. Of the ten brands, four were also selected to evaluate top coats and base coats. One red polish with no n-free claims (S1) was selected for comparison. Nail products that were explicitly marketed as an n-free nail product and sold within the U.S were selected for evaluation. A range of widely available polishes and brands commonly used in nail salons were targeted for evaluation, and the brands selected represented a significant market share of nail products sold in the U.S. Furthermore, all brands selected had been promoted in beauty magazines and nail salon trade publications as nontoxic, n-free polishes. All nail polishes were purchased online from wholesale suppliers who supply nail salons.

Figure 2 summarizes the nail code, type of polish (color polish, base coat, or top coat), as well as whether the product was marketed as a specific chemical-free product (n-free category), and a list of chemicals the manufacturer claimed were removed from the formulation.

Simulated manicure tasks

Artificial nails on the manikin's hands were painted using one of the commercially available polishes in Figure 2. For red polishes, two coats were applied to the artificial nails over a 5-min period. For top coats and base coats, one coat was applied to the artificial nails, simulating how these products would be used in salons. Nails were allowed to dry, and the concentration decay in the chamber was measured for 2 hr following the nail painting. Four replicates were

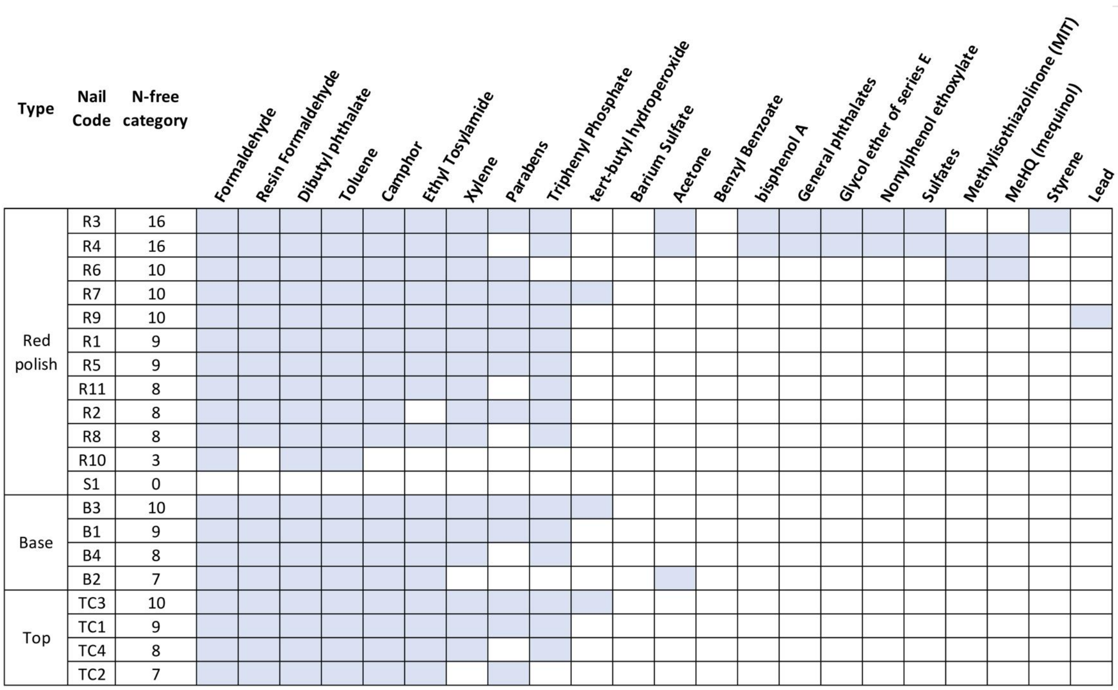

Figure 1. Chemicals and components (grey shading) excluded by the manufacturer from the nail polish products tested. Nail products categorized by type and number of chemicals/components claimed to be absent from the product (n-free claim).

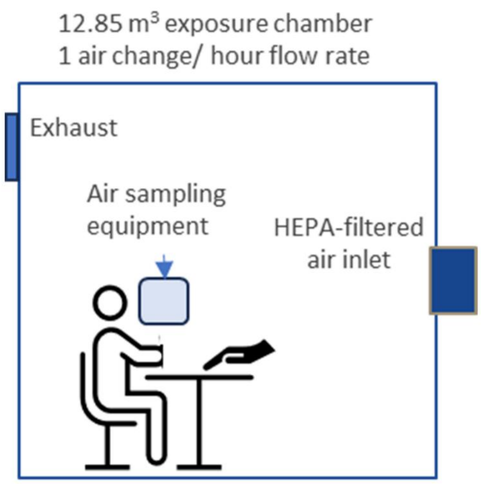

Figure 2. Schematic of the exposure chamber.

measured for each nail product. The mass of the applied product was measured by weighing the nail polish bottle before and after painting the artificial nails. The weight change was used to determine the mass of product applied. The concentration in ppm was divided by the mass of product applied to the nails to normalize the concentration by mass of product applied.

Direct reading air sampling methods

Airborne exposures were measured in the technician's breathing zone using direct reading and time-integrated methods. Background levels of gases were measured in the chamber for 10 min before starting each manicure, and all trials were background corrected. Direct reading measurements of total volatile organic compounds (TVOC) and specific chemical compounds were measured using a handheld photoionization detector (PID, Tiger, ION Science Inc., Stafford, TX) and a DX4040 Fourier transform infrared (FTIR) gas analyzer (Gasmet Technologies, Finland), respectively. The PID was factory calibrated with zero air and bump tested with 10 ppm isobutylene before use. Data logging was set at 1-sec intervals. The FTIR was used to identify and quantify 22 chemicals including formaldehyde, toluene, acetone, 1,3-butadiene, acetonitrile, acrolein, acrylic acid, benzene, butyl acetate, butyl acrylate, ethanol, ethyl acetate, ethyl acrylate, ethyl benzene, isopropanol, isopropyl acetate, methanol, methyl acrylate, methyl methacrylate, and *m*-, *o*-, and *p*-xylene. The FTIR was zero calibrated using 99.9% nitrogen gas before sampling, and data logging was set at 20-s intervals. The spectra were analyzed using Calcmet version 12.140.

Time-integrated air sampling methods

Speciated VOCs were measured using stainless steel, multibed, Air Toxics thermal desorption (TD) tubes [3½″, ¼″ o.d. (89 mm, 6.4 mm o.d), C2-AXXX-5270, Markes International, Blue Ash, OH] connected to low-flow sampling pumps (PocketPump, SKC Inc., Eighty Four, PA) with a nominal flow rate of 0.05 L min^{-1}. TD tubes were analyzed using a thermal desorption unit connected to a gas chromatograph-mass spectrometer (GC-MS) for 22 VOCs including 2-butanone, acetone, acetonitrile, benzene, butyl acetate, butyl methacrylate, 4,N,N-trimethylaniline, ethyl acetate, ethyl methacrylate, isopropyl acetate, methyl acetate, methyl methacrylate, *m* and *p* xylene, *o*-xylene, propyl acetate, and toluene. Time-integrated measurements of formaldehyde were collected using UMEx passive badges (SKC Inc., Eighty Four, PA) and analyzed following OSHA Method 1007. Dibutyl phthalate (DBP) was measured using OVS Tenax sampling tubes (20/35 mesh, 70/140 mg with a glass fiber filter, 8 × 75 mm) connected to AirChek sampling pumps (SKC Inc., Eighty Four, PA) with a nominal flow rate of 1 L/min and analyzed following OSHA Method 104. Triphenyl phosphate (TPhP) was measured using a mixed-cellulose ester (MCE, 0.8 µm pore size) filter connected to an AirChek sampling pump with a nominal flow rate of 2 L/min and analyzed following NIOSH Method 5038. TD tubes and UMEx passive badges were shipped cold, and all sample extraction and analyses (TD tubes, UMEx passive badges, OVS Tenax tubes, and MCE filters) were conducted by Bureau Veritas North America (Novi, MI).

Statistics

All statistical analyses were performed in R (version 1.4.1106, RStudio, PBC). Beta-substitution was done to replace all values between zero and the manufacturer's limit of detection (LOD) for a given compound (Ganser and Hewett 2010). The LODs for the FTIR compounds are listed in Supplemental S1. The data were more lognormal than normal; thus, all data was log-transformed before statistical analyses. Descriptive statistics (geometric mean [GM], geometric standard deviation [GSD]) were calculated for the TVOC concentrations, individual chemical components from the FTIR measurements, and time-integrated measurements. Analysis of variance (ANOVA) was used to determine if average VOC concentrations varied significantly between nail polishes, type of finish, and n-free category. Once significant differences were identified, Tukey's pairwise comparisons were computed to determine which group means were significantly different. Statistical significance was evaluated at an alpha of 0.05.

Results

Direct reading instruments

Figure 3 displays the GM concentration distribution for speciated VOC exposures from the FTIR for each nail product. The average mass applied for the red polishes was 0.5 mg, 0.45 mg for the base coats, and 0.46 mg for the top coats. Formaldehyde, benzene, and toluene were detected in all nail polishes tested, despite n-free claims, with normalized GM formaldehyde exposures ranging from 0.02 to 0.27 ppm/g, GM toluene exposures ranging from 0.07 to 0.53 ppm/g, and GM benzene exposures ranging from 0.08 to 0.75 ppm/g. Notably, normalized formaldehyde and toluene exposures did not significantly differ between different products ($p = 0.37$ and 0.07, respectively). Normalized benzene exposure was significantly higher ($p < 0.01$) for B1 compared to the red nail polishes and top coats. The only compounds with statistically significant differences between nail polishes were ethanol, isopropyl acetate, *m*-xylene, methanol, and *p*-xylene ($p < 0.01$, <0.01, <0.01, $=0.02$, and $=0.03$, respectively). For the other compounds, differences in exposure between nail polishes were minimal and not statistically significant. R2 had statistically significantly higher normalized *p*-xylene exposures compared to S1, R3, R10, R11, R1, B1, B2, TC2, TC3, and TC4 (Tukey multiple comparison). Overall, the highest exposures were measured for ethyl acetate and ethyl acrylate, whereas *o*-xylene and acrylic acid had the lowest exposures.

Nail products were categorized by their n-free claims into eight groups (standard polish with 0 or no n-free claims, 3, 7, 8, 9, 10, and 16+ n-free) and evaluated for differences in speciated VOC exposures (Figure 4). VOC exposures did not differ significantly based on n-free claims for any compound measured, except for ethyl acetate ($p = 0.03$) and *p*-xylene ($p = 0.02$). The standard polish with no n-free claims had the lowest exposure to formaldehyde (GM = 0.02 ppm/g) compared to all the other polishes evaluated, but differences were not significant. Polishes in the 10-free category had the highest formaldehyde exposures (GM = 0.09 ppm/g). The lowest toluene exposures (GM = 0.07 ppm/g) were measured for polishes in the 16+ free category. The nail polishes in the 3-free category had significantly higher exposures to ethyl acetate compared to the 8, 10, 12, and 16+ n-free categories. Benzene exposures were lowest for polishes in the 3-free category (GM = 0.07 ppm/g), whereas the 10-free category had the highest benzene exposures (GM = 0.20 ppm/g).

When grouped by polish type (top coat, base coat, or red polish), normalized, speciated VOC exposure differed significantly, with red polishes having significantly lower (*p*-value <0.01) exposures for butyl acetate, formaldehyde, and methanol compared to base coats and top coats (Figure 5). Base coats had

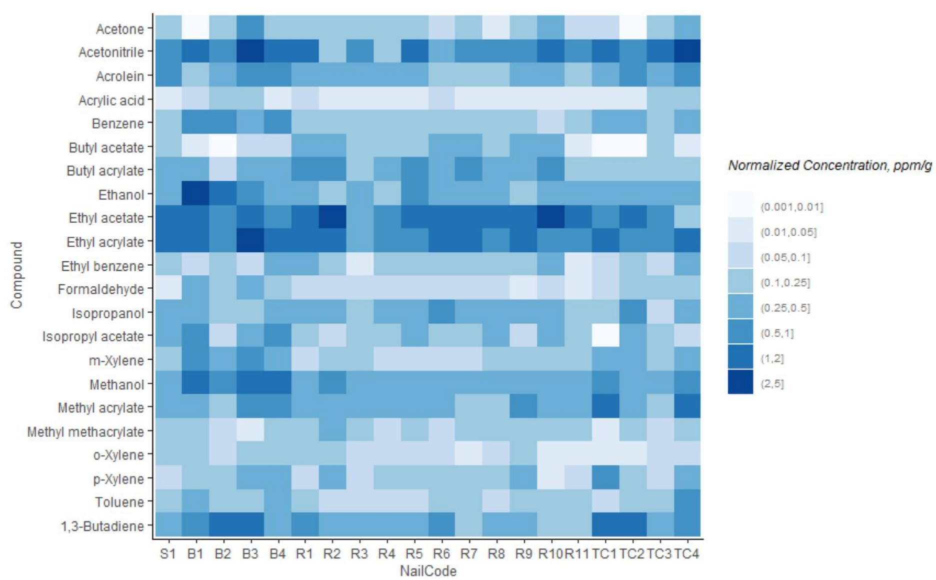

Figure 3. Heat map showing the distribution of chemicals within and among nail polishes. Geometric mean ($n = 4$) concentration (ppm) normalized by mass of polish applied from the FTIR (background-corrected).

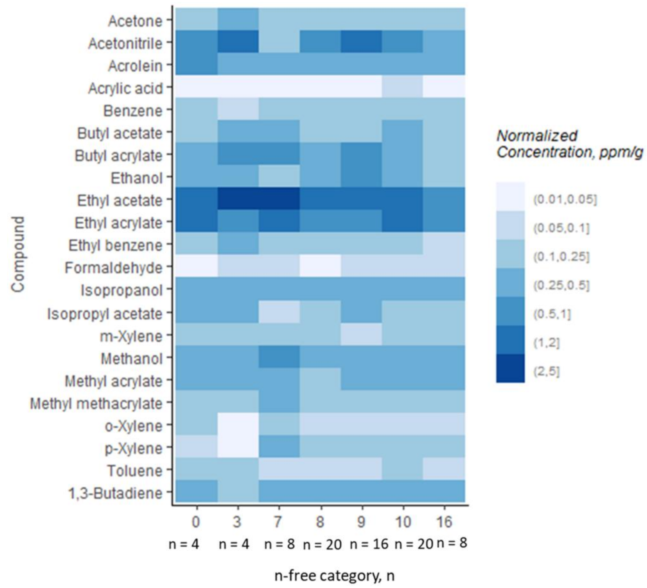

Figure 4. Heat map showing the distribution of chemicals within and among n-free categories. Geometric mean concentration (ppm) normalized by mass of polish applied from the FTIR (background-corrected).

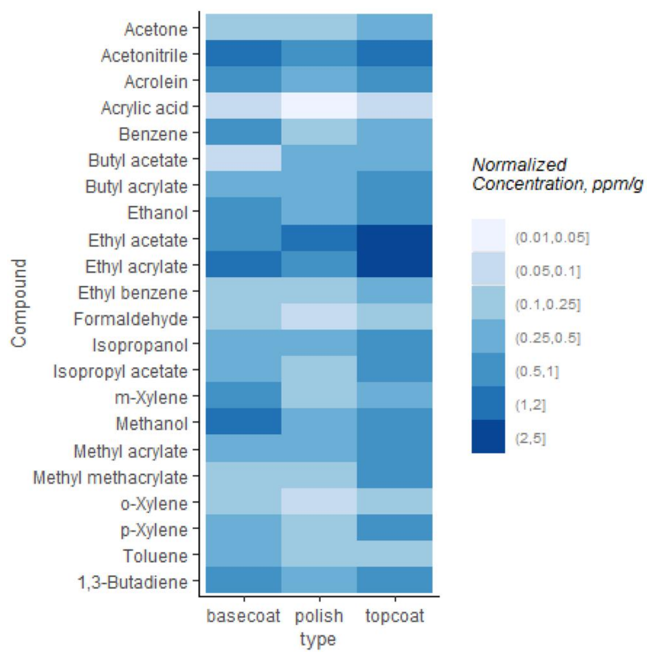

Figure 5. Heat map showing the distribution of chemicals within and among types of polish. Geometric mean concentration (ppm) normalized by mass of polish applied from the FTIR (background-corrected).

significantly higher exposures to acetonitrile, acrylic acid, benzene, ethanol, ethyl acrylate, isopropyl acetate, *m*-xylene, and methanol, compared to red polishes. Top coats had significantly higher concentrations of methyl acrylate and toluene compared to red polishes (p-value = 0.01, 0.04, respectively).

Normalized TVOC exposures ranged from 0.17 to 1.8 ppm/g (Figure 6). There were no significant differences in TVOC exposure by type of polish ($p = 0.60$) or n-free category (p-value = 0.2). Figure 7 displays the time-series data for the normalized TVOC exposures.

Time-integrated measurements

GM exposures for specific VOCs from the TD tubes are summarized in Table 1. The limit of detection for most compounds using the TD tubes was high, resulting in poor agreement between the FTIR and TD tube

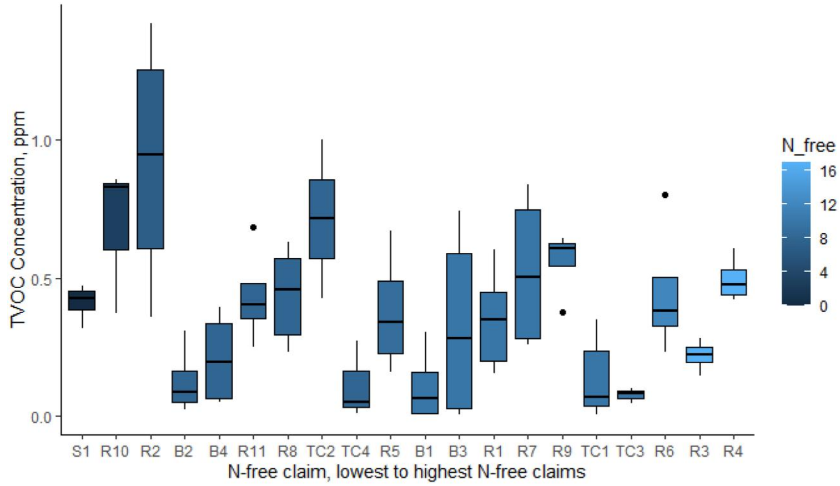

Figure 6. Boxplot displaying the TVOC exposures in ppm by nail code. The color indicates n-free category with the standard polish with no n-free claims being the darkest color, while lighter color indicates higher n-free claim.

methods. Agreements between the FTIR exposures and TD tube exposures were better for compounds at higher concentrations (butyl, ethyl, isopropyl acetate).

Neither DBP nor TPhP was detected in any of the nail polishes evaluated. Similarly, using the passive badges, formaldehyde was only detected in 25% of the samples at values below the limit of quantification, indicating this method may not be adequate for shorter task-based exposures.

Discussion

Commonly reported reproductive and respiratory hazards in nail products include formaldehyde, toluene, DBP, ethyl acetate, acetate, butyl acetate, or acetonitrile (Quiros-Alcala et al. 2019); however, product design factors such as color, texture, and drying time result in widely varying ingredients across different brands. DBP, which is used to increase the flexibility and longevity of polishes, is associated with adverse reproductive outcomes in pregnant women (Kwapniewski et al. 2008; Pak et al. 2011). Although this study did not find any exposures to DBP or triphenyl phosphate, this study did not comprehensively evaluate other phthalate exposures in n-free nail polishes. Young et al. (2018) reported triphenyl phosphate and bis(2-ethylhexyl) phthalate in polishes marketed as n-free alternatives, indicating this is an important area to investigate further.

Similar to other studies that evaluated n-free nail polishes, this study measured formaldehyde, benzene, and toluene in all polishes evaluated, despite manufacturers' claims. The Department of Toxic Substances Control (DTSC) Safer Consumer Products Program of the California Environmental Protection Agency (CalEPA) evaluated 157 nail products using gas chromatography mass spectroscopy (DTSC 2023). While this study did not focus on n-free products, they reported toluene in 17% of the product tests at concentrations ranging from 31 to 187,000 mg/mL, with topcoats, UV gel polishes, and multifunctional polishes having the highest toluene concentrations. Similarly, an earlier report from the CalEPA DTSC (2012) that evaluated 25 n-free nail products (DTSC 2012) found toluene was more frequently detected and often at higher concentrations in products marketed as n-free products compared to nail products that had no n-free claim. This study found that seven of 19 products had higher toluene concentrations compared to the standard product with no n-free claim. DTSC (2012), using EPA method 8260B, reported toluene concentrations in 10 out of 12 products claiming to be toluene-free, with concentrations ranging from 42 to 177,000 ppm. In products with no n-free claims, DTSC reported that 8 of 13 products contained toluene with concentrations up to 120,000 ppm, with an average toluene concentration of 12,354 ppm. Zhong et al. (2019) conducted static headspace sampling of 35 nail products, including lacquers, top coats, and base coats, and found ethyl acetate was the most dominant compound present, followed by n-butyl acetate, which made up over a quarter of the headspace concentration. However, this study found ethyl acetate had the highest concentration only for red lacquers. Ethyl acrylate and acetonitrile had the highest concentrations for base coats and top coats, respectively. Zhong et al. (2019) also reported substantially higher toluene concentrations in nail lacquers using a static headspace method compared to this study (7 g/m^3 compared to 0.00032 g/m^3

Table 1. Descriptive statistics (geometric mean [GM] and geometric standard deviation [GSD], and percent observations below the limit of quantification [LOQ]) for specific VOC exposures (mg m^{-3}) from thermal desorption tubes.

Compound	LOD, ng/sample	B1	B2	B3	B4	R1	R10	R11	R2	R3	R4	R5
2-Butanone	3-8	<LOD	<LOD	<LOD	<LOD	0.254 (0.222) 40%	<LOD	0.087 (0.021) 25%	<LOD	0.09 (0.031) 25%	0.276 (0.403) 0%	0.175 (0.3) 0%
Acetone	10-30	0.003 (0.002) 25%	0.01 (0.01) 0%	0.01 (0.01) 25%	0.01 (0.01) 0%	0.035 (0.027) 0%	0.012 (0.012) 0%	0.007 (0.002) 0%	0.012 (0.011) 0%	0.032 (0.053) 0%	0.008 (0.004) 0%	0.01 (0.007) 0%
Acetonitrile	5-20	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Benzene	4-6	<LOD	0.009 (0.008) 25%	<LOD	<LOD	0.016 (0.016) 40%	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Butyl acetate	2-4	1.162 (0.952) 25%	2.085 (0.348) 0%	1.674 (0.292) 0%	3.618 (0.321) 0%	3.064 (0.392) 0%	3.434 (0.501) 0%	2.608 (0.463) 0%	3.606 (0.597) 0%	3.714 (0.637) 0%	3.313 (0.059) 0%	3.964 (0.488) 0%
Butyl methacrylate	2-10	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Dimethyl p-toluidine	90-1000	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Ethyl acetate	3-5	1.614 (1.09) 25%	3.084 (0.308) 0%	3.02 (0.229) 0%	1.345 (0.24) 0%	2.811 (0.214) 0%	4.764 (0.356) 0%	4.376 (0.419) 0%	4.682 (0.444) 0%	3.591 (0.449) 0%	3.819 (0.065) 0%	3.896 (0.359) 0%
Ethyl methacrylate	2-7	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Isopropyl acetate	2-4	0.026 (0.019) 25%	0.032 (0.011) 0%	0.444 (0.095) 0%	0.226 (0.054) 0%	0.048 (0.01) 0%	0.099 (0.01) 0%	0.165 (0.018) 0%	0.219 (0.034) 0%	0.158 (0.013) 0%	0.139 (0.014) 0%	0.106 (0.023) 0%
m,p-Xylene	5-30	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Methyl acetate	3-5	0.016 (0.004) 25%	0.022 (0.021) 0%	0.034 (0.016) 0%	0.031 (0.021) 0%	0.17 (0.111) 0%	0.061 (0.041) 0%	0.078 (0.046) 0%	0.055 (0.039) 0%	0.055 (0.023) 0%	0.101 (0.17) 0%	0.1 (0.167) 0%
Methyl methacrylate	2-4	0.001 (0.002) 75%	0.004 (0.003) 25%	0.002 (0.002) 25%	0.002 (0.002) 50%	0.003 (0.002) 20%	0.003 (0.003) 33%	0.006 (0.005) 25%	0.005 (0) 0%	0.005 (0.003) 25%	0.008 (0.001) 0%	0.005 (0.001) 0%
o-Xylene	2-3	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Propyl acetate	2-4	0.006 (0.006) 25%	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	0.002 (0.001) 0%	<LOD
Toluene	2-4	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD

Compound	R6	R7	R8	R9	S1	TC1	TC2	TC3	TC4
2-Butanone	0.143 (0.053) 0%	<LOD	<LOD	0.14 (0.037) 0%	<LOD	<LOD	<LOD	<LOD	<LOD
Acetone	0.092 (0.174) 0%	0.063 (0.1) 0%	0.054 (0.103) 0%	0.011 (0.005) 0%	0.024 (0.027) 25%	0.006 (0.002) 0%	0.007 (0.003) 0%	0.009 (0.006) 0%	0.008 (0.003) 0%
Acetonitrile	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Benzene	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Butyl acetate	2.799 (0.418) 0%	3.591 (0.413) 0%	4.233 (0.436) 0%	2.738 (0.115) 0%	1.385 (0.808) 25%	1.396 (0.263) 0%	2.648 (0.396) 0%	3.012 (0.39) 0%	1.693 (0.236) 0%

(*Continued*)

Table 1. Continued.

Compound	R6	R7	R8	R9	S1	TC1	TC2	TC3	TC4
Butyl methacrylate	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Dimethyl p-toluidine	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Ethyl acetate	3.841 (0.4)	3.819 (0.282)	4.345 (0.345)	3.563 (0.095)	2.055 (1.132)	3.066 (0.338)	4.939 (0.378)	3.062 (0.304)	1.66 (0.106)
	0%	0%	0%	0%	25%	0%	0%	0%	0%
Ethyl methacrylate	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Isopropyl acetate	0.275 (0.026)	0.346 (0.113)	0.25 (0.094)	0.267 (0.063)	0.072 (0.049)	0.021 (0.002)	0.012 (0.007)	0.043 (0.01)	0.019 (0.006)
	0%	0%	0%	0%	25%	0%	0%	0%	0%
m,p-Xylene	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Methyl acetate	0.042 (0.028)	0.056 (0.025)	0.063 (0.046)	0.067 (0.034)	0.05 (0.039)	0.046 (0.023)	0.041 (0.033)	0.162 (0.118)	0.041 (0.018)
	0%	0%	0%	0%	25%	0%	0%	0%	0%
Methyl methacrylate	0.006 (0.001)	0.004 (0.003)	0.004 (0.004)	0.007 (0.002)	0.004 (0.003)	0.004 (0.003)	0.005 (0.004)	0.003 (0.003)	0.003 (0.004)
	0%	25%	40%	0%	25%	25%	25%	50%	50%
o-Xylene	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Propyl acetate	<LOD	<LOD	<LOD	0.004 (0.002)	0.759 (0.489)	<LOD	<LOD	<LOD	<LOD
				0%	25%				
Toluene	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD

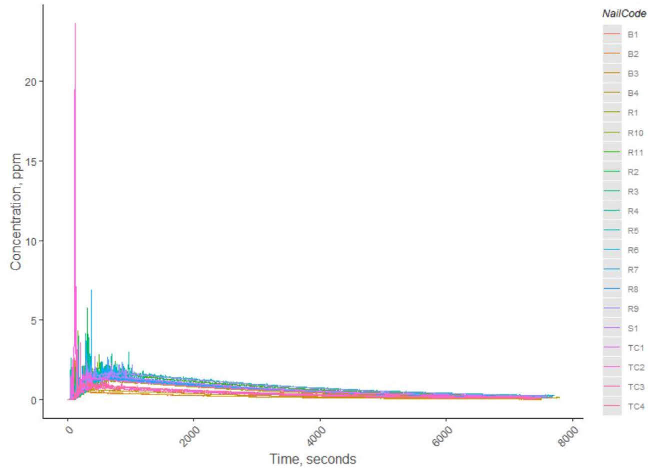

Figure 7. Time-series plot of the TVOC exposures by trial time. Color indicates the nail code.

found in this study). Furthermore, when grouped by product type, Zhong et al. (2019) did not find toluene in base coats or top coats, whereas this study found that base coats had a slightly higher toluene concentration compared to red lacquers and top coats. This study also found high concentrations of 1,3-butadiene, ranging from 0.15 ppm/g to 1.22 ppm/g. Normalized GM 1,3-butadiene concentrations were highest for base coats (0.87 pm/g) compared to red polish and top coats (0.35 and 0.58 ppm/g, respectively). Animal studies have reported adverse reproductive outcomes adverse reproductive outcomes associated with 1,3-butadiene exposure, including skeletal abnormalities and decreased fetal weight, as well as increased incidence of ovarian atrophy and testicular atrophy (Melnick and Huff 1992). In addition to reproductive effects, 1,3-butadiene is associated with increased risk of blood and lymphatic system cancers (Hughes et al. 2003). This study also found levels of acrolein, an IARC group 2A probable human carcinogen (Marques et al. 2021), were also high, with normalized GM exposures ranging from 0.21 to 1 ppm/g. These findings are concerning given the high proportion of NSWs that are females of reproductive age. Formaldehyde is a human carcinogen, a respiratory toxicant, and may cause reproductive and developmental toxicity (Duong et al. 2011). Moreover, it should be noted that the understanding of occupational reproductive hazards remains limited, with significant gaps in knowledge regarding the safety of workplace exposures for pregnant workers. Many chemicals encountered in occupational settings have not been thoroughly studied for their potential effects on reproduction or fetal development. This lack of information is compounded by challenges in determining safe exposure levels during pregnancy, as standard toxicological studies often exclude pregnant populations. Consequently, risk assessments frequently rely on extrapolations from general population data, which may not account for heightened vulnerabilities during pregnancy.

Exposures in nail salons have changed dramatically in recent years due to advances in technology and product formulations. N-free, clean, green, and nontoxic are terms used interchangeably to indicate safer alternatives to traditional nail polishes. Nail salons are increasingly using more clean or green products; 72% of salons reported using at least some green products, and 37.6% of salons report using only green, 3-free polishes (Han et al. 2022; Ma et al. 2019). Although marketed as being safer alternatives to traditional nail products, studies have found these products often contain higher concentrations of toluene and DBP compared to products with no such claims, raising concerns about worker health when using these products (Guo et al. 2012). This study found speciated VOC exposure did not differ significantly across n-free categories except for ethyl acetate and *p*-xylene, indicating that polishes with higher n-free claims are not necessarily safer compared to polishes with no claims. Furthermore, the lack of standardization in n-free labeling means products in the same n-free category may exclude completely different compounds. Formaldehyde, formaldehyde resin, DBP, toluene, and camphor were five compounds that all manufacturers excluded from their n-free products. Ethyl tosylamide, xylene, parabens, and triphenyl phosphate were the next most commonly excluded compounds. However, the lack of standardization means that the remainder of chemicals excluded varied widely between nail polishes, making it difficult to compare among the same n-free claim, as well as difficult for NSWs to understand what chemicals were excluded.

While short-term task-based exposures for all compounds and brands were low, chronic low-level VOC exposure has been associated with eye, throat, and nose irritation, dizziness, and headaches, as well as more severe outcomes such as cancer, central nervous system damage, and developmental impairment (Alford and Kumar 2021; De Oliveira et al. 2017; Wang et al. 2013; 2014; Xiong et al. 2016) and is consistent with health outcomes reported by nail technicians (Quiros-Alcala et al. 2019). Furthermore, most chemical compounds are assessed individually, and the effects of mixed exposures are not typically considered, but there may be important synergistic or additive effects to consider. Exposures resulting from working with nail products involve highly complex chemical mixtures that are generated simultaneously. Even if individual chemicals are below the occupational exposure limits, the effect of the mixed exposure may cause a variety of health effects.

Compounds emitted by nail polishes can interact with other chemicals commonly present in nail salons, leading to the formation of secondary pollutants. For example, VOCs may react with ozone or hydroxyl radicals in the air to produce secondary organic aerosols (SOAs) and aldehydes, exacerbating air quality concerns. Toluene can react with hydroxyl radicals to form benzaldehyde and other aromatic oxidation products, which may further contribute to the formation of SOAs. Formaldehyde, a reactive carbonyl compound, can undergo photolysis or react with hydroxyl radicals, leading to the production of formic acid or peroxyacyl nitrates (PANs). Ethyl acetate, an ester, may hydrolyze under acidic conditions or oxidize to acetic acid, which contributes to indoor air acidity. Additionally, the use of ammonia-based cleaning products can further complicate exposures. Ammonia can react with acidic oxidation products of VOCs emitted from nail polishes, such as formic acid or acetic acid, to form ammonium salts. These salts may be present as particulate matter, increasing $PM_{2.5}$ concentrations, which can pose health risks. These reactions are particularly problematic in poorly ventilated salons, where the accumulation of chemicals can produce heightened risks to both salon workers and clients, contributing to respiratory irritation, headaches, and long-term health issues. While this study did not evaluate the formation of secondary pollutants, they should be investigated in future studies.

Limitations

This study evaluated a comprehensive range of nail polishes marketed as nontoxic alternatives. Furthermore, this study characterized a greater number of VOCs associated with nail polish application than in many previous studies. However, there are several limitations to this study. First, this study was a controlled laboratory study; thus, concentrations in salons may be different due to different ventilation rates, varying workload requirements, variations in polishes, and additional exposure sources such as nail polish removers and artificial nail application and removal. Second, this study was limited to red polishes, base coats, and top coats. Other polishes routinely used during manicure services that could be labeled as nontoxic were not evaluated in this study.

Finally, this study was not a comprehensive evaluation of all nontoxic nail brands or polishes. Future work will evaluate products for different services (gel, dip, etc.), other nail polishes used in salons, as well as different colors.

Conclusion

NSWs may be exposed to certain hazardous compounds during nail polish application despite manufacturers' claims that product formulations do not contain those compounds. All nail polishes evaluated in this study contained formaldehyde, toluene, and benzene despite claims of being free of those compounds. Normalized geometric mean (GM) formaldehyde exposures ranged from 0.021 to 0.273 ppm/g, GM toluene exposures ranged from 0.068 to 0.534 ppm/g, and GM benzene exposures ranged from 0.076 to 0.752 ppm/g. Notably, formaldehyde, toluene, and benzene exposures did not significantly differ between different products. Nail polishes marketed as "n-free" alternatives may not reduce nail technician exposures and may emit higher concentrations of hazardous VOCs.

Further research is necessary to understand chemical exposures associated with different nail polish formulations and to ensure the reduction of hazardous chemicals. Specifically, there is a need to investigate the compounds present in the bulk nail polish liquid to determine if exposures are a result of the compound being present in the bulk material or due to secondary reactions. Additional testing to determine the presence and quantity of phthalates that may be present in the nail polishes should be conducted. Furthermore, increased product labeling transparency is needed, as well as standardization of labeling requirements, which would enable salon owners to make more informed decisions about the products they are using. Many companies include cruelty-free and vegan-free to the n-free count, which further complicates the understanding of these labels. An authoritative agency needs to set standards for n-free or alternative products to achieve standardization of labeling across manufacturers. Agencies like the EPA have the Safer Choice standard, a certification program that identifies products made with safer chemical ingredients, but as of now, no nail products have been labeled.

Acknowledgments

The authors would like to acknowledge Drs. Alyson Fortner and Emily Lee for reviewing the manuscript.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by the U.S. Government, National Institute for Occupational Safety and Health, or Centers for Disease Control and Prevention.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by NIOSH research funds.

Data availability statement

The data that support the findings of this study are available from the corresponding author, KRA, upon reasonable request.

References

Alaves VM, Sleeth DK, Thiese MS, Larson RR. 2013. Characterization of indoor air contaminants in a randomly selected set of commercial nail salons in Salt Lake County, Utah, USA. Int J Environ Health Res. 23(5):419–433. doi: 10.1080/09603123.2012.755152.

Alford KL, Kumar N. 2021. Pulmonary health effects of indoor volatile organic compounds—a meta-analysis. Int J Environ Res Public Health. 18(4):1578. doi: 10.3390/ijerph18041578.

Anderson SE, Meade BJ. 2014. Potential health effects associated with dermal exposure to occupational chemicals. Environ Health Insights. 8(Suppl 1):51–62. doi: 10.4137/EHI.S15258.

Ceballos DM, Young AS, Allen JG, Specht AJ, Nguyen VT, Craig JA, Miller M, Webster TF. 2021. Exposures in nail salons to trace elements in nail polish from impurities or pigment ingredients—a pilot study. Int J Hyg Environ Health. 232:113687. doi: 10.1016/j.ijheh.2020.113687.

Cohr K-H, Stokholm J. 1979. Toluene: a toxicologic review. Scand J Work Environ Health. 5(2):71–90. doi: 10.5271/sjweh.2664.

Cosmetics FAO. 2018. How cosmetics are not FDA-approved, but are FDA-regulated. FDA. [accessed 2021 Jan 11]. https://www.fda.gov/cosmetics/cosmetics-laws-regulations/fda-authority-over-cosmetics-how-cosmetics-are-not-fdaapproved-are-fda-regulated.

de Groot AC, Rustemeyer T. 2023. 2-hydroxyethyl methacrylate (HEMA): a clinical review of contact allergy and allergic contact dermatitis—part 1. Introduction, epidemiology, case series, and case reports. Contact Dermatitis. 89(6):401–433. doi: 10.1111/cod.14405.

De Oliveira AR, Campos Neto AdA, Bezerra de Medeiros PC, De Andrade MJ, Dos Santos NA. 2017. Chronic organic solvent exposure changes visual tracking in men and women. Front Neurosci. 11:666. doi: 10.3389/fnins.2017.00666.

DeKoven S, DeKoven J, Holness DL. 2017. (Meth) Acrylate occupational contact dermatitis in nail salon workers: a case series. J Cutan Med Surg. 21(4):340–344. doi: 10.1177/1203475417701420.

Donald JM, Hooper K, Hopenhayn-Rich C. 1991. Reproductive and developmental toxicity of toluene: a review. Environ Health Perspect. 94:237–244. doi: 10.1289/ehp.94-1567945.

DTSC. 2012. Summary of data and findings from testing of a limited number of nail products. https://dtsc.ca.gov/wpcontent/uploads/sites/31/2018/04/DTSC-Summary-of-Data-Findings-from-Testing-aLimited-Number-of-Nail-Products-April-2012.pdf.

DTSC. 2023. Laboratory study of chemicals in nail products. https://dtsc.ca.gov/wp-content/uploads/sites/31/2023/11/SCP-Report_Nail-Products-Lab-Study_Final-Accessible-New.pdf.

Duong A, Steinmaus C, McHale CM, Vaughan CP, Zhang L. 2011. Reproductive and developmental toxicity of formaldehyde: a systematic review. Mutat Res. 728(3):118–138. doi: 10.1016/j.mrrev.2011.07.003.

Freeman S, Lee MS, Gudmundsen K. 1995. Adverse contact reactions to sculptured acrylic nails: 4 case reports and a literature review. Contact Dermatitis. 33(6):381–385. doi: 10.1111/j.1600-0536.1995.tb02071.x.

Ganser GH, Hewett P. 2010. An accurate substitution method for analyzing censored data. J Occup Environ Hyg. 7(4):233–244. doi: 10.1080/15459621003609713.

Guo DF, Batarseh P, Wong J, Raphael D. 2012. Summary of data and findings from testing of a limited number of nail products. California Environmental Protection Agency, Department of Toxic Substances Control. http://legacy.library.ucsf.edu/tid/mrs76b00.

Han I, Seo JY, Barr DB, Panuwet P, Yakimavets V, D'Souza PE, An-Han H, Afshar M, Chao Y-Y. 2022. Evaluating indoor air phthalates and volatile organic compounds in nail salons in the Greater New York City Area: a pilot study. Int J Environ Res Public Health. 19(19):12411. doi: 10.3390/ijerph191912411.

Hannigan JH, Bowen SE. 2010. Reproductive toxicology and teratology of abused toluene. Syst Biol Reprod Med. 56(2):184–200. doi: 10.3109/19396360903377195.

Harrichandra A, Roelofs C, Pavilonis B. 2020. Occupational exposure and ventilation assessment in New York City nail salons. Ann Work Expo Health. 64(5):468–478. doi: 10.1093/annweh/wxaa035.

Heaton T, Hurst LK, Amiri A, Lungu CT, Oh J. 2019. Laboratory estimation of occupational exposures to volatile organic compounds during nail polish application. Workplace Health Saf. 67(6):288–293. doi: 10.1177/2165079918821701.

Hemmer W, Focke M, Wantke F, Götz M, Jarisch R. 1996. Allergic contact dermatitis to artificial fingernails prepared from UV light-cured acrylates. J Am Acad Dermatol. 35(3 Pt 1):377–380. doi: 10.1016/s0190-9622(96)90600-3.

Hines CJ, Nilsen Hopf NB, Deddens JA, Calafat AM, Silva MJ, Grote AA, Sammons DL. 2009. Urinary phthalate metabolite concentrations among workers in selected industries: a pilot biomonitoring study. Ann Occup Hyg. 53(1):1–17. doi: 10.1093/annhyg/men066.

Hughes K, Meek M, Walker M, Beauchamp R. 2003. 1,3-Butadiene: exposure estimation, hazard characterization, and exposure-response analysis. J Toxicol Environ Health B Crit Rev. 6(1):55–83. doi: 10.1080/10937400306478.

Kiec-Swierczynska M, Krecisz B, Chomiczewska-Skora D. 2013. Occupational contact dermatitis to acrylates in a manicurist. Occup Med (Lond). 63(5):380–382. doi: 10.1093/occmed/kqt059.

Kucharczyk M, Słowik-Rylska M, Cyran-Stemplewska S, Gieroń M, Nowak-Starz G, Kręcisz B. 2021. Acrylates as a significant causes of allergic contact dermatitis–new sources of exposure. Postepy Dermatol Alergol. 38(4):555–560. doi: 10.5114/ada.2020.95848.

Kwapniewski R, Kozaczka S, Hauser R, Silva MJ, Calafat AM, Duty SM. 2008. Occupational exposure to dibutyl phthalate among manicurists. J Occup Environ Med. 50(6):705–711. doi: 10.1097/JOM.0b013e3181651571.

Ma GX, Wei Z, Husni R, Do P, Zhou K, Rhee J, Tan Y, Navder K, Yeh M-C. 2019. Characterizing occupational health risks and chemical exposures among Asian nail salon workers on the East Coast of the United States. J Community Health. 44(6):1168–1179. doi: 10.1007/s10900-019-00702-0.

Marques MM, Beland FA, Lachenmeier DW, Phillips DH, Chung F-L, Dorman DC, Elmore SE, Hammond SK, Krstev S, Linhart I, et al. 2021. Carcinogenicity of acrolein, crotonaldehyde, and arecoline. The Lancet Oncology. 22(1):19–20. doi: 10.1016/S1470-2045(20)30727-0.

Melnick RL, Huff J. 1992. 1,3-Butadiene: toxicity and carcinogenicity in laboratory animals and in humans. Rev Environ Contam Toxicol. 124:111–144.

NPD Group. 2018. US prestige beauty industry sales grow 6 percent in 2018, reports the NPD Group. Makeup In-Depth Consumer Report 2018. http://npd.com/wps/portal/npd/us/news/press-releases/2019/us–prestige-beauty-industry-sales-grow-6-percent-in-2018–reports-the-npd-group.

Pak VM, McCauley LA, Pinto-Martin J. 2011. Phthalate exposures and human health concerns: a review and implications for practice. AAOHN J. 59(5):228–235. doi: 10.1177/216507991105900505.

Park S-A, Gwak S, Choi S. 2014. Assessment of occupational symptoms and chemical exposures for nail salon technicians in Daegu City, Korea. J Prev Med Public Health. 47(3):169–176. doi: 10.3961/jpmph.2014.47.3.169.

Quach T, Varshavsky J, Von Behren J, Garcia E, Tong M, Nguyen T, Tran A, Gunier R, Reynolds P. 2013. Reducing chemical exposures in nail salons through owner and worker trainings: an exploratory intervention study. Am J Ind Med. 56(7):806–817. doi: 10.1002/ajim.22146.

Quiros-Alcala L, Pollack AZ, Tchangalova N, DeSantiago M, Kavi LK. 2019. Occupational exposures among hair and nail salon workers: a scoping review. Curr Environ Health Rep. 6(4):269–285. doi: 10.1007/s40572-019-00247-3.

Semple S. 2004. Dermal exposure to chemicals in the workplace: just how important is skin absorption? Occup Environ Med. 61(4):376–382. doi: 10.1136/oem.2003.010645.

Sharma P, Waheed S, Nguyen V, Stepick V, Orellana R, Katz L, Kim S. 2018. Nail files: a study of nail salon workers and industry in the United States. UCLA: Institute for Research on Labor and Employment. https://escholarship.org/uc/item/9kj023cj.

Stefaniak AB, Bowers LN, Knepp AK, Virji MA, Birch EM, Ham JE, Wells JR, Qi C, Schwegler-Berry D, Friend S, 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.

Tran HM, Bui HTM, Thoumsang S, Wangwongwatana S, Nguyen HPA, Phung D. 2022. Health risk assessment of volatile organic compounds exposure among nail salon workers in Vietnam. Hum Ecol Risk Assess Int J. 28(2): 265–280. doi: 10.1080/10807039.2022.2044285.

Wang F, Li C, Liu W, Jin Y. 2013. Oxidative damage and genotoxic effect in mice caused by sub-chronic exposure to low-dose volatile organic compounds. Inhal Toxicol. 25(5):235–242. doi: 10.3109/08958378.2013.779767.

Wang F, Li C, Liu W, Jin Y, Guo L. 2014. Effects of sub-chronic exposure to low-dose volatile organic compounds on lung inflammation in mice. Environ Toxicol. 29(9): 1089–1097. doi: 10.1002/tox.21844.

White H, Khan K, Lau C, Leung H, Montgomery D, Rohlman DS. 2015. Identifying health and safety concerns in Southeast Asian immigrant nail salon workers. Arch Environ Occup Health. 70(4):196–203. doi: 10.1080/19338244.2013.853644.

Xiong F, Li Q, Zhou B, Huang J, Liang G, Zhang L, Ma S, Qing L, Liang L, Su J, et al. 2016. Oxidative stress and genotoxicity of long-term occupational exposure to low levels of BTEX in gas station workers. Int J Environ Res Public Health. 13(12):1212. doi: 10.3390/ijerph13121212.

Young AS, Allen JG, Kim U-J, Seller S, Webster TF, Kannan K, Ceballos DM. 2018. Phthalate and organophosphate plasticizers in nail polish: evaluation of labels and ingredients. Environ Sci Technol. 52(21):12841–12850. doi: 10.1021/acs.est.8b04495.

Zhang J, Mason M, Nong G, Zhu JJ, Howard EM, Shaw CY, Brown S. 2001. Standard practice for full-scale chamber determination of volatile organic emissions from indoor materials/products. Philadelphia, PA: American Society of Testing and Materials.

Zhong L, Batterman S, Milando CW. 2019. VOC sources and exposures in nail salons: a pilot study in Michigan, USA. Int Arch Occup Environ Health. 92(1):141–153. doi: 10.1007/s00420-018-1353-0.