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Review Article

Human Health Risks from Textile Chemicals: A Critical Review of Recent Evidence (2019-2025)

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Global textile production, driven by consumer demand, raises significant concerns about chemical exposures from clothing and related products. This review synthesizes evidence (2019–2025) on hazardous substances in textiles, including dyes, plasticizers, per- and polyfluoroalkyl substances (PFAS), and metals, and identifies and categorizes their associated human health risks. Focusing on dermal absorption as the primary exposure route, risks to vulnerable populations (e.g., infants, pregnant women) and gaps in regulatory frameworks are highlighted. The current analysis reveals that chronic exposure to chemical mixtures in textiles remains poorly understood, with current safety assessments often neglecting synergistic effects. Key findings include elevated risks from phthalates in infant clothing, PFAS in water-repellent fabrics, and carcinogenic aromatic amines from azo dyes. We underscore the urgency of harmonized global regulations, advanced biomonitoring, and sustainable alternatives (e.g., enzymatic dyes, biodegradable finishes). Public awareness initiatives and stricter enforcement of certifications (e.g., OEKO-TEX®, GOTS) are critical to mitigating risks. ***Interdisciplinary collaboration among textile technologists, toxicologists, and public health experts is essential to develop safer textile alternatives and integrate health-centric approaches into sustainability agendas, safeguarding consumers, workers, and ecosystems.***

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1. Introduction

The global textile and clothing industry serves as a cornerstone of economic activity and fulfills essential consumer needs for functional and aesthetic products. However, its extensive production chain,

doi.org/10.32388/0GADTB.2

encompassing spinning, dyeing, finishing, and distribution, relies substantially on synthetic chemicals, many carrying significant environmental and health risks. While fabrics range from natural to synthetic, the latter frequently involve complex chemical additives such as dyes, flame retardants, softeners, and heavy metals. These substances can persist in final textile products, potentially contributing to long-term health hazards[1][2][3][4][5].

Textile manufacturing significantly contributes to environmental pollution, especially through the discharge of untreated wastewater containing toxic dyes, carcinogenic aromatic amines (AAs), and heavy metals such as chromium, lead, and antimony[6][7][8]. Beyond ecosystem degradation, these pollutants pose risks to human health through occupational exposures and via residual chemical transfer to consumers[9][10][11]. Workers in textile manufacturing face heightened risks due to prolonged and direct exposure to these chemicals during production processes, such as dyeing and finishing, compared to consumers whose exposure primarily occurs through dermal contact with finished products[11]. For example, widely used azo dyes can degrade into carcinogenic AAs like o-toluidine and 4-aminobiphenyl, classified as Group 1 carcinogens by the IARC[12]. Disperse dyes, common in synthetic fiber coloration, are associated with allergic contact dermatitis and sensitization[13][14]. Furthermore, emerging research indicates that trace elements (e.g., nickel, cobalt) and endocrine-disrupting chemicals (EDCs) such as bisphenol analogs (BPA, BPS, BPF) can migrate from clothing to skin under normal wear conditions, raising concerns about chronic dermal exposure pathways (Figure 1)[15][16][17][18].

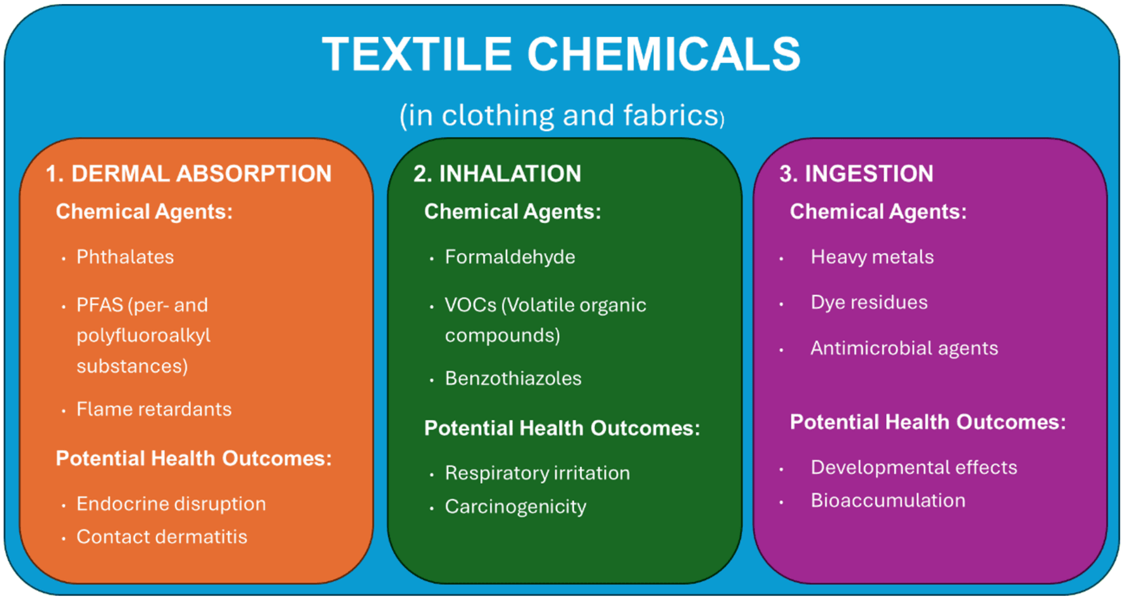

Figure 1. Schematic representation of the primary exposure pathways for textile-associated chemicals.

Although regulatory frameworks like the EU REACH legislation restrict certain hazardous substances, such as 22 specific carcinogenic AAs derived from azo dyes[19], significant gaps remain in comprehending the full spectrum of chemical risks. Vulnerable populations, particularly children and infants, exhibit heightened susceptibility due to immature detoxification pathways and extended skin contact duration with garments[10][20].

In a previous review[6], we highlighted the human health risks from inorganic and organic chemicals in textiles, noting research focus mainly on occupational settings over consumer exposure. While allergic reactions were commonly studied, other potential health effects received less attention. The present review has been focused on chemicals likely present in clothing, including flame retardants, trace elements, AAs, quinoline derivatives, bisphenols, benzothiazoles/benzotriazoles, phthalates, formaldehyde, and metal nanoparticles, concluding that dermal exposure is non-negligible and could pose unacceptable cancer risks under certain conditions.

Given the dynamic nature of the textile industry and its materials and processes, this updated review aims to synthesize evidence published since our last overview[6], focusing on health risks from textile-related chemical exposures. By identifying critical research gaps, this paper underscores the need for interdisciplinary research and sustainable innovations to mitigate risks within this globally integral industry.

2. Search Strategy

A comprehensive literature search was performed to identify studies concerning human health risks associated with chemical exposure from textiles. The databases PubMed, Scopus, Web of Science, and Google Scholar were queried for relevant peer-reviewed articles published between December 2018 and March 2025 (updating Rovira and Domingo[6]). Search terms were systematically combined using Boolean operators (e.g., "textiles AND human exposure," "clothing AND toxic chemicals," "dyes AND risk assessment") to retrieve relevant studies. Initial searches were screened for duplicates and relevance based on titles and abstracts. Full-text reviews assessed studies for inclusion based on English language, focus on textile chemical exposures, and human health outcomes. Reference lists of selected articles were manually screened, adding 12 additional publications. This structured approach ensures transparency and reproducibility for future research.

3. Results

3.1. Phthalates

Phthalate esters (PAEs) are widely employed as plasticizers in consumer products, including textiles, to enhance flexibility and durability. However, concerns exist regarding their potential adverse health effects, such as endocrine disruption, reproductive toxicity, and carcinogenicity. Infants are considered a particularly susceptible group due to their developing physiology and propensity for close contact with materials like cotton, which can readily adsorb PAEs. Phthalates were detected in 92% of textile samples across studies, with median concentrations ranging from 2.92 to 4,150 ng/g, significantly higher than metals (65% detection, median 4.2–1844 mg/kg) but comparable to PFAS (89% detection, median 0.25–153,000 ng/g)[21][22][23]. This section summarizes the available scientific information from January 2019 to March 2025, highlighting key findings on exposure pathways, health risks, and regulatory gaps.

Li et al.[21] tracked PAE accumulation in infant cotton clothing in China, finding high detection rates and concentrations from production through initial wear, suggesting significant adsorption of ambient PAEs. Standard laundering practices were found insufficient for complete removal. The median total PAE concentration was 4.15 µg/g, dominated by di-(2-ethylhexyl) phthalate (DEHP). However, risk assessments indicated that dibutyl phthalate (DBP) and di-iso-butyl phthalate (DiBP) contributed most significantly to estimated daily intakes (EDIs) for infants via dermal absorption, identified as the primary exposure route. Clothing was highlighted as a major contributor to dermal PAE exposure compared to air or dust, with detected DEHP levels potentially posing health risks. Complementary work by Tang et al. [22] examined PAEs in new preschool children's clothing from seven Asian countries. Analysis of 15 PAEs confirmed their extensive presence, with total concentrations ranging from 2.92 to 223 µg/g. DEHP, DiBP, and DBP were the most abundant (median contributions: 48.5%, 13.6%, and 13.4%, respectively). While total PAE levels varied by item type, DEHP was consistently identified as the dominant compound, raising concerns about long-term dermal exposure.

The widespread use of PAEs in polymers led to investigations of face masks as potential exposure sources, which were particularly relevant during the COVID-19 pandemic. Xie et al.[24] detected twelve PAEs in 56 internationally sourced mask samples, with total levels ranging from 115 to 37,700 ng/g. Corresponding EDIs via masks (3.71 to 639 ng/kg bw/day) were 4-5 times higher for toddlers than adults. While calculated non-carcinogenic risks were generally acceptable, a large proportion (89.3%) of samples showed potential carcinogenic effects, implying moderate risk compared to other skin-contact products. Similarly, Wang et al.[25] measured PAEs (251 to 3830 ng/g) and organophosphate esters (OPEs) (36.7 to 855 ng/g) in masks from Chinese markets, observing lower levels in toddler masks. Simulated inhalation experiments confirmed PAE release over 12 hours, although estimated exposure risks remained below thresholds.

Expanding to other textiles, Zhang et al.[26] analyzed PAEs in new face towels in China. Total concentrations ranged from less than the method detection limit (<MDL) to 2388 ng/g (median: 173.2 ng/g). Interestingly, PAE content was higher in used towels and in coral velvet compared to cotton. While water washing reduced some PAEs, detergent washing paradoxically increased levels. Hazard quotients (HQ) and hazard indices (HI) indicated negligible non-carcinogenic risk. However, DEHP, the only identified carcinogen among the target PAEs, necessitates attention regarding potential long-term risks.

Providing regulatory context, the EU REACH regulation restricts four phthalates (DEHP, DBP, BBP, DiBP) in textiles to 0.1% by weight, while the US Consumer Product Safety Improvement Act (CPSIA) limits six phthalates in children’s products to 0.1% (CPSC, 2024). Recently, Aldegunde-Louzao et al.[27] reported on a large-scale screening (2014–2020) of ortho-phthalates in textiles submitted for quality control in Southern Europe and North Africa. Analysis of 4729 samples showed high compliance (97.25%) with EU regulations. Noncompliant samples typically contained multiple phthalates, whereas compliant ones usually contained only one. DEHP, DiNP, and DBP were most frequently detected. A temporal trend revealed decreasing DEHP levels alongside increasing DiNP and DiDP, suggesting substitution practices.

A recent multi-media exposure study in China[23] included clothing as a direct exposure source for covered skin. Total PAE concentrations in clothing (3.71 to 30.1 μg/g) aligned with previous findings[21][22], with DEHP, DBP, and DiBP being commonly detected. Material analysis indicated higher average levels of DMP, DEP, and DBP in cotton versus non-cotton items, and concentrations (except DEP) were generally higher in colored clothing, potentially linked to PAE use as solvents or dye components.

In turn, Aldegunde-Louzao et al.[28] provided a comprehensive review of PAEs in textiles over the last decade (2014-2023), covering types, roles, legislation, analysis, exposure modeling, and health risks. Earlier reviews by Lucaccioni et al.[29] and Chang et al.[9] summarized human health effects. Thus, Lucaccioni et al.[29] emphasized the risks during critical developmental windows (prenatal/early postnatal), potentially disrupting neuroendocrine systems (e.g., thyroid signaling) and increasing risks of neurodevelopmental disorders (ADHD, autism, reduced IQ). Moreover, Chang et al.[9] found consistent epidemiological evidence linking PAE exposure (especially DEHP) to reduced sperm quality and ADHD symptoms but noted insufficient or inconsistent evidence for links to cardiovascular disease, thyroid issues, respiratory problems, diabetes, obesity, kidney disease, intelligence deficits, or other reproductive system outcomes.

3.2. Per- and Polyfluoroalkyl Compounds (PFAS)

Per- and polyfluoroalkyl compounds, known as PFAS, are widely used in textile finishing agents (TFAs) for oil, water, and stain repellency. This makes the textile sector a major source of PFAS emissions. Analytical techniques like liquid chromatography-tandem mass spectrometry (LC-MS/MS) are commonly used for PFAS detection due to their high sensitivity (detection limits ~0.01–0.1 ng/g), though challenges remain in quantifying non-extractable polymeric PFAS[30]. Mumtaz et al.[31] found significant perfluorooctane sulfonate (PFOS) levels (0.37 mg/L) in TFAs produced via electrochemical fluorination, while products using short-chain PFAS-based telomerization contained perfluorooctanoic acid (PFOA) at concentrations (mean 0.29 mg/L) exceeding the European Chemical Agency guidelines (0.025 mg/L). This section synthesizes recent findings on PFAS migration, and potential health risks, emphasizing the need for stricter regulations and alternative chemistries.

Zhu and Kannan[32] measured 13 perfluoroalkyl acids (PFAAs) in 160 US textile samples. Using simple solvent extraction, summed PFAA concentrations (ΣPFAA) ranged widely (<LOD to 63.7 μg/m^2), averaging 3.18 μg/m^2. Oxidative treatment of extracts yielded ΣPFAA concentrations tenfold higher, indicating the presence of PFAA precursors, particularly those generating C4-C5 PFCAs. While calculated infant dermal

exposure was below US EPA reference doses, that study pioneered oxidative treatment for textile PFAS analysis, revealing hidden precursors. Schellenberger et al.[33] studied polyamide fabrics treated with side-chain fluorinated polymers (SFPs) under outdoor weathering in Australia. Exposure to natural stressors, abrasion, and washing led to the loss of PFAS-containing microfibers and the formation/loss of low molecular weight PFAS, coinciding with reduced water repellency and color loss. Oxidative conversion confirmed potential PFAA formation from mobile residuals, with post-weathering emissions sometimes exceeding regulatory limits. The study concluded indicating that PFAS emissions during weathering involve both precursor transformation and polymeric PFAS release via degradation/fiber loss.

Focusing on children's products, Xia et al.[34] analyzed 72 US items marketed as stain-resistant (especially school uniforms). Total fluorine screening (PIGE) followed by targeted analysis identified PFAS (predominantly 6:2 fluorotelomer alcohol, 6:2 FTOH) in all products. Concentrations ranged from 0.250 to 153,000 ng/g (median 117 ng/g). Levels in school uniforms were significantly higher than in bibs or swimsuits, comparable to outdoor wear, and higher in 100% cotton uniforms than synthetic blends. Hydrolysis and total oxidizable precursor assays confirmed abundant PFAA precursors. Estimated median potential dermal exposure for children, via uniforms, was 1.03 ng/kg bw/day. Substance flow analysis suggested ~3 tons/year of PFAS used in US children's uniforms (mostly polymeric, but ~0.1 ton/year mobile, nonpolymeric). Van der Veen et al.[35] examined how aging, washing, and tumble drying affect extractable PFAS in durable water-repellent (DWR) coatings (based on FC-6 and FC-8 SFPs) on polyamide and polyester. Aging generally increased PFAA concentrations, while washing decreased them, but could sometimes increase extractable volatile PFAS. Tumble drying had little effect. The study concluded that aging and washing release PFAS into the environment. Highlighting analytical challenges, Zweigle et al.[30] showed limitations of standard extraction for non-extractable SFPs in DWR finishes. Comparing oxidation (dTOP, PhotoTOP), hydrolysis (THP), standard extraction, extractable organic fluorine (EOF), and total fluorine (TF) methods, the authors found direct oxidation/hydrolysis captured large TF fractions present as side-chains (yielding concentrations up to >1000 mg F/kg, ~25-50x higher than extract-based methods). This conversion contradicted some previous findings and indicated continued use of long-chain SFPs.

A broader review by Dewapriya et al.[36] analyzed PFAS data from consumer products over the past decade (52 studies, 1040 products). 107 PFAS across 15 categories were identified, with textiles showing the greatest diversity (72 types), and high average concentrations among personal use items. Contextually, human PFAS exposure occurs via contaminated food, water, air, consumer products, and dust[37][38]. PFAS lifecycle leakage contaminates environments, leading to health risks including certain cancers, thyroid dysfunction, cholesterol changes, and reduced birth weight[39]. A NASEM[40] report recommended offering PFAS blood testing to potentially highly exposed individuals, advising screening/monitoring if levels indicate increased risk.

Yang et al.[41] reviewed recent PFAS data in consumer products including textiles, emphasizing the need for research on skin absorption and health effects for textiles due to prolonged contact. They detailed PFAS loss mechanisms during weathering: fabric fragment loss, SFP main-chain degradation, side-chain transformation (low-molecular-weight PFAS loss), and mobile impurity loss, leading to diminished water resistance.

3.3. Metals

Although clothing can contribute to the body's metal burden, research remains limited. Inductively coupled plasma-mass spectrometry (ICP-MS) is the preferred analytical method for detecting metals in textiles due to its high sensitivity (detection limits ~0.01–0.1 mg/kg) and ability to quantify multiple elements simultaneously[42]. This section reviews recent studies on metal migration, exposure pathways, and health risks. Herrero et al.[43] measured trace elements in denim, finding magnesium and manganese highest in artificial sweat migration tests. Indigo dye migrated more from dark blue fabrics (3.22-7.76 mg/g). While overall risks were within limits, antimony exposure from polyester items yielded a HQ of 0.3. A subsequent study on swimsuits[2] found titanium highest overall (mean 1844 mg/kg), especially in polyamide (3759 mg/kg). Elevated chromium occurred in black polyamide (624-932 mg/kg). Non-cancer risks were acceptable, but carcinogenic risks for chromium approached or exceeded the 10^{-5} threshold for babies and children-girls. Examining 120 clothing items for pregnant women and infants in Spain, Herrero et al.[20] found aluminum, zinc, and titanium at median values of 27.6, 5.6, 4.2 mg/kg, respectively. Titanium exposure exceeded the safety threshold (HQ > 1) for pregnant women (1.13) and newborns (1.22).

Chen et al.[44] investigated metals in preschool clothing from four Asian regions, finding higher nickel and chromium, but lower lead and cadmium compared to other textiles. Cadmium was higher in black clothing, and cobalt higher in non-cotton. Chinese-manufactured items had significantly higher lead, but overall risks remained acceptable. Bruzzoniti et al.[42] developed an analytical method for hexavalent chromium (Cr(VI)) in textiles using Na3PO4 extraction, achieving good recovery and low quantitation limits (0.017 mg/kg). Application revealed Cr(VI) only in panties at low levels (0.028 mg/kg), posing no significant risk. Foschi et al.[45] used combined GC-MS and ICP-MS for volatile organic compounds and trace metals. Principal component analysis differentiated samples by origin, with cotton content being key. While most samples complied with regulations, some exceeded copper and nickel thresholds, highlighting quality control needs.

3.4. Dyes

Dyes are essential for coloring textiles, leather, and plastics. Textile dyes are broadly classified as hydrophilic or hydrophobic. Azo dyes account for nearly 50% of global dye usage but are increasingly restricted due to health and environmental concerns, particularly their potential for bioaccumulation associated with constituent aromatic AAs and heavy metals. Gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS) are widely used for dye analysis, with GC-MS offering high specificity for volatile AAs (detection limits ~0.5–5 µg/g) and LC-MS excelling in detecting polar dye metabolites[46]. Human exposure occurs via food chain and inhalation. Organic dyes and their components can adversely affect reproductive, renal, hepatic, and central nervous systems, potentially initiating processes leading to severe diseases like cancer[47].

Indigo is a widely used natural dye, which poses challenges in its conventional synthesis (using toxic precursors like aniline, formaldehyde, hydrogen cyanide) and application (requiring reducing agents). Bio-indigo synthesis via enzymatic routes, particularly using flavin-containing monooxygenases (FMOs), shows promise but faces hurdles: limitations of microbial chassis (e.g., *E. coli*), toxicity of the intermediate indole, cost of L-tryptophan substrate, poor water-solubility of indigo, need for chemical reducers, and lower yields/higher costs compared to chemical synthesis[48]. Azo dyes in textiles and leather present risks because human metabolic processes (enzymes, gut microbiome) can cleave the azo bond, releasing constituent AAs, some known or suspected mutagens/carcinogens. While some hazardous azo dyes are banned, many remain in use without systematic risk evaluation. In relation to this, Keshava et al.[46] conducted a systematic evidence map (SEM) on 30 market-relevant azo dyes, identifying 187 studies (54 humans, 78 animals, 61 genotoxicity). Toxicological data were abundant for three dyes (also food additives) but sparse for five others. Integrating diverse data sources (e.g., ECHA REACH, US EPA CompTox) into the SEM proved challenging. The compiled evidence aimed to inform potential regulatory needs and future research.

Reviews by Islam et al.[49] and Sudarshan et al.[50] examined the broader impacts of textile dyes, covering structure, pollution sources, treatment methods (chemical, biological, physical, hybrid), classification, toxicity, and bioremediation strategies (microalgae, bacteria). In turn, Ramamurthy et al.[8] specifically reviewed the genotoxic impact of azo dyes (e.g., Sudan dyes, Basic Red 51, Disperse Yellow 7, Congo Red) on aquatic ecosystems and human health, highlighting evidence for carcinogenicity, chromosomal abnormalities, adverse physiological/neurobehavioral changes, and spermatogenesis disruption, underscoring the need for comprehensive toxicological assessment.

Many AAs released from azo dyes lack toxicity data and regulation, despite structural similarities to known carcinogens. Souza et al.[7] assessed 40 non-regulated AAs in 240 clothing items from Spain and Brazil. While Spanish samples had low levels, AAs were common in Brazilian clothes, with 75 items exceeding a hazardous threshold (30 mg/kg) for at least one AA. Aniline was most frequent (82%). Suspected mutagenic AAs (e.g., o-aminobenzenesulfonic acid, p-phenylenediamine) were detected, especially in synthetic fibers. While the overall calculated hazard index was low under medium-bound scenarios, it approached 1 (0.998) for Brazilian pregnant women under upper-bound conditions, potentially underestimating risk by omitting other exposure routes and co-occurring chemicals. Subsequently, Souza et al.[51] measured 20 regulated AAs in clothes, again finding higher levels in Brazilian samples. Sixteen regulated AAs were detected above 5 mg/kg in Brazil vs. eleven in Spain, particularly in synthetic/pink items. Dermal exposure assessment indicated the highest risks for 2,4-diaminoanisole (toddlers, Brazil) and 4,4-oxydianiline (newborns, Spain). Non-cancer risks for 4,4-benzidine exposure in Brazilian toddlers were high (calculated at 14.5). Potential cancer risks were identified for 3,3-dichlorobenzidine (newborns/toddlers, Brazil), prompting calls for continuous monitoring. Further work by Souza et al.[52] measured 58 AAs in urine from 300 pregnant Brazilian women, correlating levels with DNA damage (8OHdG). Eight AAs (including regulated 2,6-dimethylaniline, 2,4-diaminotoluene) were detected in 100% of samples. Aniline levels correlated with other AAs, suggesting multiple sources. Both tobacco smoke and dermal contact with azo dye-containing clothes appeared as significant contributors to urinary AAs. A regression model ($R^2 = 0.772$) linked specific regulated AAs (2-naphthylamine, 4-aminobiphenyl), nicotine, smoking, age, and region to increased 8OHdG levels, stressing the need for more human exposure data, especially for non-regulated carcinogenic AAs.

Recently, Nishi et al.[53] used effect-directed analysis (EDA) to investigate aryl hydrocarbon receptor (AhR) agonists in textiles. A cell-based assay detected AhR activation in extracts from two of ten commercial products. Chemical fractionation identified the agonist in one product. Further testing identified

Disperse Blue 291 and Disperse Blue 373 as novel AhR agonists, highlighting textiles as overlooked sources and necessitating detailed exposure/toxicity evaluations.

3.5. Bisphenols

Bisphenols (BPs) are typically non-intentionally added compounds in textiles, but they can be a source of human exposure via prolonged skin contact. Freire et al.[16] analyzed 32 pairs of infant/child socks (1-48 months) from Spain. BPA was found in 90.6% of samples (<0.70 to 3736 ng/g), with levels ~25-fold higher in those socks with more cotton. Parabens were also detected (ethyl- 100%, methyl- 81.0%, propyl- 43.7%). Estrogenic activity was present in 83.3% of socks from one store, while anti-androgenic activity was detected in six socks. Estimated dermal BPA exposure was highest for 36–48-month children (median = 17.6 pg/kg/day). Herrero et al.[54] examined BPA and analogs (BPS, BPB, BPF) in 120 clothing items for pregnant women, newborns, and toddlers in Spain. BPA traces occurred in all samples (median 7.43 ng/g), being highest in polyester. Conventional cotton had higher BP concentrations than organic cotton (significant difference for BPS: 1.24 vs. 0.76 ng/g). Although pregnant women had higher estimated BP exposure than children, non-carcinogenic risks remained below thresholds. Jurikova et al. [17] compared 57 adult textile samples (33 recycled, 24 conventional). BPA and BPS varied widely (BPA: <0.050-625 ng/g; BPS: 0.277-2,474 ng/g). Median BPA was higher in recycled textiles (13.5 ng/g) than in conventional (7.66 ng/g), while BPS showed the opposite trend (1.85 ng/g recycled vs. 3.42 ng/g conventional), suggesting a shift from BPA to BPS manufacturing. Washing reduced BP concentrations, but exposure from sweat-wet textiles frequently exceeded the EFSA tolerable daily intake of 0.2 ng/kg bw/day for BPA. Wang et al.[55] investigated ten bisphenols in Chinese-made underwear, finding total concentrations from 13.9 to 52,967 ng/g. BPS, BPF, and BPA were dominant (median proportions of 53.2%, 24.4%, and 22.2%, respectively), with higher levels in darker items. Migration rates into artificial sweat were higher for BPF (39.1%) and BPS (25.2%) than for BPA (6.58%). While non-carcinogenic risks were acceptable, estimated exposure to BPS and BPF from underwear contributed notably (2.53-12.0% and 11.8-38.2%, respectively) to total human exposure.

3.6. Other Chemicals

Clothing manufacturing utilizes numerous chemicals, but residual levels in finished garments are often poorly documented. Prolonged skin contact makes clothing a potential source of exposure to migrating hazardous compounds. Carlsson et al.[56] analyzed 24 imported garments in Sweden, most frequently finding benzothiazole and quinoline. Nitroanilines (suspected mutagens/skin sensitizers) and quinoline (carcinogen) were found at the highest concentrations, sometimes nearing or exceeding the 50 µg/g REACH limit for quinoline. Other detected compounds with potential for skin uptake included acridine, benzotriazoles, phthalates, nitrophenols, and organophosphates. That pilot study highlighted priority chemicals for further investigations (skin transfer, absorption, systemic exposure), and it suggested insufficient control of chemicals in imported garments. Recognizing that large-volume chemicals like arylamines, quinolines, and halogenated nitrobenzenes (potential mutagens, carcinogens, skin sensitizers) used in textile production may persist in final products, Carlsson et al.[57] developed an automated thermal desorption–gas chromatography/mass spectrometry (ATD-GC/MS) method for the screening of textiles. With a method quantification limit (MQL) below 5 µg/g using a 5 mg sample, the method was well-suited for detecting EU-regulated quinoline and arylamines. Pilot application detected various chemicals in synthetic fibers, including arylamines, with some halogenated dinitroanilines up to 300 µg/g (exceeding limits for similar EU REACH regulated arylamines). A subsequent study of the same research group[58], confirmed that common halogenated textile pollutants migrate into artificial sweat and are absorbed by skin *in vitro*. Migration levels were up to 390 times higher than literature values. Mutagenicity (Ames test) was observed for 2,5-dinitrochlorobenzene and 3,5-dinitrobromobenzene. 2,5-dinitrochlorobenzene and 2,6-dichlorobenzene-1,4-diamine were identified as skin sensitizers. Although individual compound risks seemed to be low, even at high levels, the authors cautioned about potential risks from complex mixtures during prolonged daily exposure.

Interest in "eco-friendly" clothing is rising, but formaldehyde (a known carcinogen) may still be present. Herrero et al.[5] detected formaldehyde in 20% of analyzed eco-friendly and conventional clothing items in Spain (mean 8.96 mg/kg). Surprisingly, levels were higher in eco-friendly garments (10.4 vs 8.23 mg/kg), especially undergarments. While levels were below legal limits (<75 mg/kg), and calculated risks acceptable (highest for babies), the potential co-presence of other toxics remained. Washing effectively removed formaldehyde, leading to a recommendation to wash clothes before first use. Ji et al.[59] screened clothing for additives (synthetic antioxidants, OPEs, phthalates), detecting 93 of 98 target chemicals in 78 items. Synthetic antioxidants were found at significantly higher concentrations (median 25.1 µg/g) than OPEs/phthalates. Chemical profiles differed significantly between cotton and synthetic fabrics, with concentrations found to be three times higher in children's clothing compared to adults. Dermal contact via sweat was identified as a major exposure pathway for 2,4-di-tert-butyl-phenol, advising against re-wearing sweaty clothes. The study estimated significant environmental release via laundry wastewater

(11.2 tons/year, in China), with 2,6-di-tert-butyl-p-benzoquinone a major contributor (20.4% input to WWTPs). While switching to non-halogenated alternatives for textile finishing was encouraged, their impacts need study. Martí et al.[60] compared conventional and alternative flame retardant (FR) treatments on cotton. Both functioned as FRs but affected thermal behavior differently. Dermal toxicity tests indicated both were safe under applied conditions. The alternative FR appeared potentially safer given its higher concentration in the textile. Addressing recycling challenges, Åström et al.[61] used comprehensive screening to track chemicals during the upcycling of post-consumer garments into cellulose nanocrystals (CNCs). Transfer of toxic substances to CNCs was limited. Only a few plasticizers (DEHP, DBP) were strongly attached, requiring risk assessment for final application. However, the recovered polyester fraction retained most identified chemicals, suggesting potential unsuitability for many applications due to hazardous chemical leaching risks.

3.7. Microfibers and Nanoparticles

Recent literature, predominantly composed of review articles, explores the presence and implications of microfibers and nanoparticles (NPs) in textiles. Licina et al.[62] reviewed how clothing acts as a vehicle for exposure to molecular chemicals and abiotic/biotic particles (microbes, allergens). The authors explored contaminant acquisition, retention, and transmission, identifying sources from manufacturing byproducts, environmental adhesion, and occupational settings. While clothing could be protective, it could also mediate significant exposures, influenced by clothing type/history, contaminant properties, and wear/care practices.

Textile microfibers can be synthetic, semi-synthetic, or modified natural materials, often containing chemical additives like dyes (e.g., synthetic indigo in denim)[63]. Saleem and Zeidi[64] reviewed nanomaterial applications in textiles (nanofinishing, nanocoatings, nanofibers, nanocomposites), stressing the need for comprehensive risk assessment due to prolonged skin contact and recommending better awareness and regulation for nanomaterial-containing textile waste. Moreover, Ramasamy and Subramanian[65] examined measures to control microfiber pollution, finding that finer yarns and compact fabric structures reduced shedding, while mechanical finishes like shearing increased it by damaging the fabric structure. Chemical coatings significantly reduced release. Commercial laundry filters offered some efficiency but were considered control, not prevention. Controlling textile parameters during production was deemed most effective. Peryasamy[66] highlighted that microfibers from functionalized textiles were often non-biodegradable and toxic due to added dyes, chemicals, and nanomaterials, posing risks to humans and ecosystems. In turn, Lant et al.[67] experimentally showed that colder, quicker wash cycles could indirectly reduce microfiber release by extending clothing lifetime, decreasing the frequency of high-shedding initial washes.

Regarding specifically NPs, widely used TiO_2 NPs raise health/environmental concerns. Rashid et al. [68] reviewed TiO_2 NP exposure and toxicity, concluding that risk-benefit analysis based on intended use is crucial, requiring appropriate risk management and regulation to mitigate toxicity. Wang et al. [69] investigated microfiber release during textile processing (prewashing, dyeing, heat setting, rinsing) in Malaysia. Polyester microfiber emissions during wet processing were similar in magnitude to laundering emissions, whereas cotton emissions were significantly lower during wet processing, but higher overall (combined processing and laundering) than polyester, although this ratio decreased with increasing polyester production. Silver nanoparticles (AgNPs), used for antimicrobial properties, can be released during wear, causing dermal exposure. With low derived-no-effect-limit values (0.01-0.0375 mg/kg-bw), even low exposures may pose risks. Koivisto et al.[70] investigated AgNP release using artificial sweat/mechanical stress, modeling exposure from masks, suits, and gloves. Calculated dermal intake risk characterization ratios (RCR) varied by product, duration, and skin type, reaching 0.9 for full-body wear (worst-case), underscoring the need for comprehensive assessments.

3.8. Textiles and Clothing: Dermal Contact and Allergies

Allergic reactions are typically caused by substances added to enhance material qualities, not the fibers themselves. The textile dye mix (TDM) in baseline patch test series is valuable, but testing with patients' own materials is often needed. Svedman et al.[71] provided an updated review covering irritant and allergic textile dermatitis, clinical recommendations, and patch testing. Dermatitis often resembles endogenous eczema, localized to areas of garment contact (e.g., skin folds). Disperse azo dyes are the most frequent culprits, but other substances can trigger allergies. Formaldehyde and thiazolinones used in production are known allergens. Diagnosis involves *in vivo* (patch testing), or *in vitro* (cytokine detection) methods. Research has also explored medical textiles with enhanced properties (e.g., antimicrobial sutures, growth factor-releasing dressings)[72]. Disperse dyes (DDs) are common causes of textile allergy. Linauskiene et al.[73] found TDM-positive individuals reacted to synthetic garment extracts even without the pure DDs present in the TDM 6.6% mix, suggesting other culprit haptens exist. Medical textiles also pose allergy risks (contact dermatitis, respiratory issues) from fibers, dyes, or finishes, particularly for items used on sensitive areas (masks, dressings, etc.)[74]. Antiallergic materials and finishes offer potential solutions, but thorough safety testing is vital. The standard TDM 6.6% contains multiple DDs. Disperse Orange 3 (DO 3) is the most frequent allergen and often cross-reacts with para-phenylenediamine (PPD). Isaksson et al.[75] tested if DO 3 could be removed from TDM. Testing 1481 patients, the researchers found 3.6% allergy to TDM 6.6% vs. 3.0% to TDM 7.0% (without DO 3). All 26 DO 3-positive patients also reacted to PPD. It was concluded that TDM 7.0% could replace TDM 6.6% in the Swedish baseline series, if used alongside PPD 1.0%. Nijman et al.[13] demonstrated the value of testing individual textile dyes alongside the textile dye mix (TDM), revealing that among 209 suspected patients, 54 (25.8%) tested positive for TDM or individual dyes, with Disperse Orange 3 (9.6%) and Disperse Blue 106 (4.8%) being the most frequently identified allergens. Testing individual dyes identified relevant allergies missed by TDM alone in ~36% of clinically relevant cases. In Spain, Hernandez Fernandez et al.[14] analyzed TDM sensitivity (2019-2022). Of 6128 patients, 3.3% were TDM-positive, correlating with hairdressing/beauty occupations and specific dermatitis locations. 57% of TDM-positive patients also reacted to PPD, being DO 3 the most frequent positive dye (16%). One in six cases positive to the textile dye series would have been missed using TDM alone.

On the other hand, Guo et al.[76] examined alkylphenol ethoxylates (APEOs) in unwashed textiles. Total concentrations ranged from 113.21–1431.18 mg/kg (nonylphenol ethoxylates dominant). Toddlers exhibited the highest dermal exposure to APEOs in new garments, with HIs reaching 10.62 for toddlers and 8.37 for infants at maximum concentrations, both exceeding safety thresholds (HI > 1). Washing garments before use reduced APEO concentrations by up to 90%, significantly mitigating exposure risks. Ruiz Sánchez et al.[77] described chronic prurigo (CP) associated with allergic contact dermatitis (ACD) from fragrances (4 cases) and textile dyes (2 cases). Allergen avoidance led to improvement. Histology suggested Th2-driven immunity (fragrance-ACD) and Th2/Th17 involvement (azo dye-ACD). The study demonstrated that textile-derived dyes and fragrances can induce papular dermatitis characteristic of contact pruritus (CP), underscoring the importance of patch testing in patients with idiopathic or clinically suspected allergic contact dermatitis.

4. Discussion

This review highlights significant advancements in understanding textile-related chemical exposures since our previous assessment[6], while underscoring persistent challenges and emerging risks. Earlier work emphasized occupational hazards and allergic reactions, but recent evidence shifts focus to consumer exposures, particularly for vulnerable populations. For instance, while dermal absorption was theorized as a pathway in 2019, studies now quantify its dominance: phthalate exposure via infant clothing contributes 58–73% of total intake[21][23], and PFAS in school uniforms exposes children to 1.03 ng/kg bw/day[34]. These findings validate earlier concerns about prolonged skin contact but reveal far greater specificity in exposure routes and magnitudes.

Regulatory frameworks have evolved but remain inconsistent. The EU's 2025 PFAS restrictions and the US TSCA regulations target long-chain PFAS, but short-chain alternatives like 6:2 FTOH remain prevalent, with unresolved safety concerns[78]. Similarly, while EU REACH bans 22 carcinogenic AAs from azo dyes, the US lacks equivalent federal restrictions, relying on state-level measures. In turn, Brazilian textiles exhibit 4,4-benzidine levels 14× higher than Spanish equivalents, with toddler hazard indices reaching 14.5[51], a stark contrast to the 2019 findings, which lacked region-specific risk comparisons. Similarly, OEKO-TEX® now enforces stricter limits for BPA (10 mg/kg), yet recycled textiles retain 87% of original additives like DEHP[61], highlighting gaps in circular economy safeguards. Certification schemes like OEKO-TEX® and GOTS are critical but face challenges in global enforcement, particularly in low-income countries where compliance monitoring is limited[3].

Emerging chemical classes since 2019, halogenated nitrobenzenes, AhR agonists like Disperse Blue 291/373, and bisphenol analogs, now complicate risk profiles. For example, recycled textiles contain 1.8× higher BPA levels than conventional items[17] and sweat exposure to BPF/BPS exceeds EFSA's TDI by 220%[55]. Mixture toxicity, a theoretical concern in 2019, now has empirical support: co-occurring PAEs and PFAS in face masks show additive oxidative stress effects[25], while halogenated dinitroanilines in synthetic fabrics demonstrate mutagenicity in Ames tests[58]. Conflicting findings, such as higher formaldehyde in eco-friendly garments[5] versus lower risks in organic cotton[54], suggest that "sustainable" labels do not guarantee safety, necessitating rigorous chemical screening. Vulnerable populations face quantified risks absent in prior reviews. Titanium exposure from polyester clothing yields HQ > 1 for newborns[20], and antimony intake from swimsuits reaches 30% of TDI for infants[2]. Biomonitoring data further link urinary aromatic amines in Brazilian pregnant women to DNA damage (8OHdG), with regression models implicating textile-derived 2-naphthylamine and 4-aminobiphenyl[52]. These findings underscore the inadequacy of single-chemical risk assessments, a limitation noted in 2019 that remains unresolved.

Analytical advancements since 2019, such as ATD-GC/MS[59] and oxidative conversion methods[32], now detect 93 additives per assay and reveal hidden PFAS precursors. However, these tools also expose regulatory blind spots: 70% of EU textile alerts in 2023 involved chromium(VI) exceedances[3], and “eco-friendly” garments contain 26% higher formaldehyde than conventional items[5]. Such paradoxes challenge sustainability narratives and emphasize the need for transparency in certification schemes.

Geographic inequities in chemical regulation and enforcement persist. For example, while Spanish textiles largely comply with REACH limits, Brazilian samples frequently exceed hazardous thresholds for non-regulated aromatic amines[7]. This disparity is particularly pronounced in low-income countries, where lax enforcement and reliance on non-compliant supply chains exacerbate risks[3]. This disparity mirrors global manufacturing trends, where lower-income regions absorb higher chemical risks, a dynamic absent from our previous analysis[6]. Harmonizing standards remains critical, as evidenced by the EU’s proposed PFAS ban by 2028, which faces implementation hurdles in supply chains reliant on non-compliant producers.

Moving forward, three priorities emerge. First, biomonitoring must expand to track textile-specific biomarkers, particularly for mixtures. Second, predictive toxicological models should replace outdated single-compound frameworks, integrating real-world exposure scenarios (e.g., sweat interactions, microfiber release). For example, textile technologists could collaborate with toxicologists to develop enzymatic dyes that minimize AA release, while public health experts design exposure models for low-income communities. Third, regulatory policies must balance innovation with precaution, as substitutions like short-chain PFAS or BPF often replicate the hazards they replace[78]. The rise of effect-directed analysis (EDA) tools identifying novel hazards like AhR agonists[53] further underscores the need for proactive hazard screening.

In summary, while the 2019 review laid critical groundwork, this update reveals a landscape where regulatory advances are outpaced by chemical innovation and global inequities. The field must transition from hazard identification to prevention, prioritizing health-centered design in textiles and equitable enforcement of safety standards.

5. Conclusion

Textiles represent a significant and underestimated source of daily chemical exposure. While acute effects like allergies are recognized, the long-term systemic health consequences of chronic, low-dose exposure to complex chemical mixtures in clothing remain largely uncharacterized and potentially substantial. Specific research gaps include longitudinal studies on low-dose mixture exposures, child-specific toxicity thresholds (e.g., for PFAS and bisphenols), and comprehensive risk assessments in low-income countries where regulatory oversight is limited. The present review highlights the urgent need for a coordinated, multidisciplinary approach involving researchers, regulators, industry, and the public. Key priorities must include developing and adopting safer alternatives, advancing human biomonitoring for realistic exposure assessment, strengthening global regulatory coherence and enforcement, and empowering consumers with transparent information. Actionable recommendations include mandating pre-market chemical screening for all textiles, expanding certification schemes to include mixture toxicity, and fostering collaborations between textile engineers and health scientists. Human health must become a central pillar in the evolving discourse on textile sustainability to ensure the protection of consumers and workers worldwide.

Chemical Group	**Common Uses**	**Exposure Routes**	**Health Risks**	**Regulatory Status**
Phthalates	Plasticizers in fibers	Dermal, inhalation	Endocrine disruption, reproductive toxicity, carcinogenicity	Restricted in some regions (e.g., EU REACH); substitution trends observed
PFAS	Water/oil repellents	Dermal, inhalation	Carcinogenicity, thyroid dysfunction, immune suppression	Some PFAS banned/restricted; debates on short-chain PFAS ongoing
Metals	Dyes, pigments, antimicrobials	Dermal, ingestion	Neurotoxicity, carcinogenicity (e.g., Cr, Cd), skin sensitization	Variable regulation; strict limits for Pb and Cd in textiles
Azo Dyes	Colorants	Dermal, ingestion	Release carcinogenic amines, allergic dermatitis	Certain azo dyes banned in EU; others remain unregulated
Bisphenols	Non-intentional additives	Dermal	Endocrine disruption, developmental effects	BPA restricted; increasing use of substitutes like BPS and BPF
Formaldehyde	Wrinkle-resistant finishes	Dermal, inhalation	Carcinogenicity, skin irritation, respiratory issues	Legal limits exist but enforcement varies globally

Table 1. Summary of Key Chemical Groups in Textiles and Their Health Risks

Statements and Declarations

Authorship

All authors have contributed equally to the conception and design of the manuscript, drafting and critically revising the article, and approving the final version for submission.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence this paper.

References

1. ^*Fan Y, Chen Q, Wang Z, Zhang X, Zhao J, Huang X, Wei P, Hu P, Cao Z (2022). "Identifying dermal exposure as the dominant pathway of children's exposure to flame retardants in kindergartens." Sci Total Environ. 808:152004. doi:10.1016/j.scitotenv.2021.*
2. a, b, c*Herrero M, Rovira J, Esplugas R, Nadal M, Domingo JL (2020). "Human exposure to trace elements, aromatic amines and formaldehyde in swimsuits: Assessment of the health risks." Environ Res. 181:108951. doi: 10.1016/j.envres.2019.108951.*
3. a, b, c, d*EEA, European Environment Agency (2024). PFAS in textiles in Europe's circular economy. https://www.eea.europa.eu/en/analysis/publications/pfas-in-textiles-in-europes-circular-economy (accessed: March 10, 2025).*
4. ^*Herrero M, González N, Rovira J, Marquès M, Domingo JL, Abalos M, Abad E, Nadal M. Health risk assessment of polychlorinated biphenyls (PCBs) in baby clothes. A preliminary study. Environ Pollut. 2022a Aug 15; 307:119506. doi: 10.1016/j.envpol.2022.119506.*
5. a, b, c, d*Herrero M, González N, Rovira J, Marquès M, Domingo JL, Nadal M (2022). "Early-Life Exposure to Formaldehyde through Clothing." Toxics. 10(7):361. doi:10.3390/toxics10070361.*
6. a, b, c, d, e, f*Rovira J, Domingo JL (2019). "Human health risks due to exposure to inorganic and organic chemicals from textiles: a review." Environ Res. 168:62-69. doi:10.1016/j.envres.2018.09.027.*
7. a, b, c*Souza MCO, González N, Herrero M, Marquès M, Rovira J, Domingo JL, Barbosa F Jr, Nadal M (2023a). "Non-regulated aromatic amines in clothing purchased in Spain and Brazil: screening-level exposure and health impact assessment." J Environ Manage. 339:117905. doi:10.1016/j.jenvman.2023.117905.*

8. a, b *Ramamurthy K, Priya PS, Murugan R, Arockiaraj J (2024). "Hues of risk: investigating genotoxicity and environmental impacts of azo textile dyes." Environ Sci Pollut Res Int. 31(23):33190-33211. doi:10.1007/s11356-024-33444-1.*
9. a, b, c *Chang WH, Herianto S, Lee CC, Hung H, Chen HL (2021). "The effects of phthalate ester exposure on human health: A review." Sci Total Environ. 786:147371. doi:10.1016/j.scitotenv.2021.147371.*
10. a, b *Chen H, Chai M, Cheng J, Wang Y, Tang Z (2022). "Occurrence and health implications of heavy metals in preschool children's clothing manufactured in four Asian regions." Ecotoxicol Environ Saf. 245:114121. doi:10.1016/j.ecoenv.2022.114121.*
11. a, b *Manickam P, Deepthi V (2021). "Chemical hazards in textiles." In: Chemical management in textiles and fashion. Woodhead Publishing. 19-52. doi:10.1016/B978-0-12-820494-8.00002-2.*
12. ^ *IARC (2021). Monographs on the evaluation of carcinogenic risks to humans, volume 127: Some aromatic amines and related compounds. Lyon, France.*
13. a, b *Nijman L, Rustemeyer T, Franken SM, Ipenburg NA (2023). "The prevalence and relevance of patch testing with textile dyes." Contact Dermatitis. 88(3):220-229. doi:10.1111/cod.14260.*
14. a, b *Hernández Fernández CP, Borrego L, Giménez Arnau AM, Zaragoza Ninet V, Sanz Sánchez T, Miquel Miquel FJ, González Pérez R, Silvestre Salvador JF, Córdoba Guijarro S, Carrascosa Carrillo JM, Gatica Ortega ME, Ruiz González I, Mercader García P, Tous Romero F, Serra Baldrich E, Pastor-Nieto MA, Rodríguez Serna M, Sánchez Pérez J, Sánchez Gilo A, Melé Ninot G, Sánchez-Pedreño Guillén P, de Vega Martínez M, Descalzo MÁG, Doval IG (2024). "Sensitization to textile dyes in Spain: Epidemiological situation (2019-2022)." Contact Dermatitis. 90(5):486-494. doi:10.1111/cod.14513.*
15. ^ *Domingo JL (1989). "Cobalt in the environment and its toxicological implications." Rev Environ Contam Toxicol. 108:105-32. doi:10.1007/978-1-4613-8850-0_3.*
16. a, b *Freire C, Molina-Molina JM, Iribarne-Durán LM, Jiménez-Díaz I, Vela-Soria F, Mustieles V, Arrebola JP, Fernández MF, Artacho-Cordón F, Olea N (2019). "Concentrations of bisphenol A and parabens in socks for infants and young children in Spain and their hormone-like activities." Environ Int. 127:592-600. doi:10.1016/j.envint.2019.04.013.*
17. a, b, c *Jurikova M, Dvorakova D, Bechynska K, Pulkrabova J (2024). "Bisphenols in daily clothes from conventional and recycled material: evaluation of dermal exposure to potentially toxic substances." Environ Sci Pollut Res Int. 31(43):55663-55675. doi:10.1007/s11356-024-34904-4.*
18. ^ *Tian W, Ren P, Hou X, Fan B, Wang Y, Pei L, Wang H, Chen Z, Jin Y (2025). "Porous nickel-cobalt phosphate with oxygen-rich vacancies in situ grown on dopamine-modified cellulose textiles as self-supporting high*

mass loadings supercapacitor electrode." J Colloid Interface Sci. 677(Pt B):626-636. doi:10.1016/j.jcis.2024.08.112.

19. ^*ECHA, European Chemical Agency (2024). Substances restricted under REACH. https://echa.europa.eu/substances-restricted-under-reach (accessed: March 12, 2025).*
20. a, b, c*Herrero M, Rovira J, González N, Marquès M, Barbosa F, Sierra J, Domingo JL, Nadal M, Souza MCO (2023). "Clothing as a potential exposure source of trace elements during early life." Environ Res. 233:116479. doi:10.1016/j.envres.2023.116479.*
21. a, b, c, d*Li HL, Ma WL, Liu LY, Zhang Z, Sverko E, Zhang ZF, Song WW, Sun Y, Li YF (2019). "Phthalates in infant cotton clothing: occurrence and implications for human exposure." Sci Total Environ. 683:109-115. doi:10.1016/j.scitotenv.2019.05.132.*
22. a, b, c*Tang Z, Chai M, Wang Y, Cheng J (2020). "Phthalates in preschool children's clothing manufactured in seven Asian countries: occurrence, profiles and potential health risks." J Hazard Mater. 387:121681. doi:10.1016/j.jhazmat.2019.121681.*
23. a, b, c*Zhu H, Zheng N, Chen C, Li N, An Q, Zhang W, Lin Q, Xiu Z, Sun S, Li X, Li Y, Wang S (2024). "Multi-source exposure and health risks of phthalates among university students in Northeastern China." Sci Total Environ. 913:169701. doi:10.1016/j.scitotenv.2023.169701.*
24. ^*Xie H, Han W, Xie Q, Xu T, Zhu M, Chen J (2022). "Face mask-a potential source of phthalate exposure for human." J Hazard Mater. 422:126848. doi:10.1016/j.jhazmat.2021.*
25. a, b*Wang C, Su ZH, He MJ (2023). "Dynamic variation and inhalation exposure of organophosphates esters and phthalic acid esters in face masks." Environ Pollut. 316(Pt 2):120703. doi:10.1016/j.envpol.2022.120703.*
26. ^*Zhang W, Zheng N, Wang S, Sun S, An Q, Li X, Li Z, Ji Y, Li Y, Pan J (2023). "Characteristics and health risks of population exposure to phthalates via the use of face towels." J Environ Sci (China). 130:1-13. doi:10.1016/j.jes.2022.10.016.*
27. ^*Aldegunde-Louzao N, López PP, Aira ML, Latorre CH (2022). "Seven-year-long screening of phthalate esters in clothing and textile products from a quality control laboratory." Textile Research Journal. 93(7-8):1670-1685. doi:10.1177/00405175221135619.*
28. ^*Aldegunde-Louzao N, Lolo-Aira M, Herrero-Latorre C (2024). "Phthalate esters in clothing: A review." Environ Toxicol Pharmacol. 108:104457. doi:10.1016/j.etap.2024.104457.*
29. a, b*Lucaccioni L, Trevisani V, Passini E, Righi B, Plessi C, Predieri B, Iughetti L (2021). "Perinatal exposure to phthalates: from endocrine to neurodevelopment effects." Int J Mol Sci. 22(8):4063. doi:10.3390/ijms22084063.*

30. a, b*Zweigle J, Capitain C, Simon F, Roesch P, Bugsel B, Zwiener C (2023). "Non-extractable PFAS in functional textiles - characterization by complementary methods: oxidation, hydrolysis, and fluorine sum parameters." Environ Sci Process Impacts. 25(8):1298-1310. doi:10.1039/d3em00131h.*
31. ^*Mumtaz M, Bao Y, Li W, Kong L, Huang J, Yu G (2019). "Screening of textile finishing agents available on the Chinese market: an important source of per-and polyfluoroalkyl substances to the environment." Front Environ Sci Eng. 13:67. doi:10.1007/s11783-019-1145-0.*
32. a, b*Zhu H, Kannan K (2020). "Total oxidizable precursor assay in the determination of perfluoroalkyl acids in textiles collected from the United States." Environ Pollut. 265(Pt B):114940. doi:10.1016/j.envpol.2020.114940.*
33. ^*Schellenberger S, Liagkouridis I, Awad R, Khan S, Plassmann M, Peters G, Benskin JP, Cousins IT (2022). "An outdoor aging study to investigate the release of per- and polyfluoroalkyl substances (PFAS) from functional textiles." Environ Sci Technol. 56(6):3471-3479. doi:10.1021/acs.est.1c06812.*
34. a, b*Xia C, Diamond ML, Peaslee GF, Peng H, Blum A, Wang Z, Shalin A, Whitehead HD, Green M, Schwartz-Narbonne H, Yang D, Venier M (2022). "Per- and polyfluoroalkyl substances in North American school uniforms." Environ Sci Technol. 56(19):13845-13857. doi:10.1021/acs.est.2c02111.*
35. ^*van der Veen I, Schellenberger S, Hanning AC, Stare A, de Boer J, Weiss JM, Leonards PEG (2022). "Fate of per- and polyfluoroalkyl substances from durable water-repellent clothing during use." Environ Sci Technol. 56(9):5886-5897. doi:10.1021/acs.est.1c07876.*
36. ^*Dewapriya P, Chadwick L, Gorji SG, Schulze B, Valsecchi S, Samanipour S, Thomas KV, Kaserzon SL (2023). "Per-and polyfluoroalkyl substances (PFAS) in consumer products: current knowledge and research gaps." J Hazard Mat Lett. 4:100086. doi:10.1016/j.hazl.2023.100086.*
37. ^*Domingo JL, Nadal M (2017). "Per- and Polyfluoroalkyl Substances (PFASs) in Food and Human Dietary Intake: A Review of the Recent Scientific Literature." J Agric Food Chem. 65(3):533-543. doi:10.1021/acs.jafc.6b04683.*
38. ^*González N, Domingo JL (2025). "PFC/PFAS concentrations in human milk and infant exposure through lactation: a comprehensive review of the scientific literature." Arch Toxicol. doi:10.1007/s00204-025-03980-x.*
39. ^*Nadal M, Domingo JL (2025). "Non-invasive matrices for the human biomonitoring of PFAS: an updated review of the scientific literature." Toxics. 13(2):134. doi:10.3390/toxics13020134.*
40. ^*NASEM (2022). Guidance on PFAS exposure, testing, and clinical follow-up. Washington, DC, USA: The National Academies Press. doi:10.17226/26156.*

41. ^*Yang Y, Wang J, Tang S, Qiu J, Luo Y, Yang C, Lai X, Wang Q, Cao H (2025). "Per- and polyfluoroalkyl substances (PFAS) in consumer products: an overview of the occurrence, migration, and exposure assessment." Molecules. 30(5):994. doi:10.3390/molecules30050994.*

42. a, b*Bruzzoniti MC, Schilirò T, Gea M, Rivoira L (2024). "Determination of hexavalent chromium in textiles of daily use by ion chromatography and dermal risk assessment." Environ Res. 242:117731. doi:10.1016/j.envres.2023.117731.*

43. ^*Herrero M, Rovira J, Nadal M, Domingo JL (2019). "Risk assessment due to dermal exposure of trace elements and indigo dye in jeans: Migration to artificial sweat." Environ Res. 172:310-318. doi:10.1016/j.envres.2019.02.030.*

44. ^*Chen H, Cheng J, Li Y, Li Y, Wang J, Tang Z (2023). "Occurrence and potential release of heavy metals in female underwear manufactured in China: Implication for women's health." Chemosphere. 342:140165. doi:10.1016/j.chemosphere.2023.140165.*

45. ^*Foschi M, Colantoni V, Reale S, Scappaticci C, D'Archivio AA, Biancolillo A (2025). "Analysis of volatile organic compounds in textiles: Insights from GC–MS with metal content assessment using ICP-MS." Applied Sciences (2076-3417). 15(3).*

46. a, b*Keshava C, Nicolai S, Vulimiri SV, Cruz FA, Ghoreishi N, Knueppel S, Lenzner A, Tarnow P, Vanselow JT, Schulz B, Persad A, Baker N, Thayer KA, Williams AJ, Pirow R (2023). "Application of systematic evidence mapping to identify available data on the potential human health hazards of selected market-relevant azo dyes." Environ Int. 176:107952. doi:10.1016/j.envint.2023.107952.*

47. ^*Dutta S, Adhikary S, Bhattacharya S, Roy D, Chatterjee S, Chakraborty A, Banerjee D, Ganguly A, Nanda S, Rajak P (2024). "Contamination of textile dyes in aquatic environment: Adverse impacts on aquatic ecosystem and human health, and its management using bioremediation." J Environ Manage. 353:120103. doi:10.1016/j.jenvman.2024.120103.*

48. ^*Fan C, Xie Z, Zheng D, Zhang R, Li Y, Shi J, Cheng M, Wang Y, Zhou Y, Zhan Y, Yan Y (2024). "Overview of indigo biosynthesis by Flavin-containing Monooxygenases: History, industrialization challenges, and strategies." Biotechnol Adv. 73(Jul-Aug):108374. doi:10.1016/j.biotechadv.2024.108374.*

49. ^*Islam T, Repon MR, Islam T, Sarwar Z, Rahman MM (2023). "Impact of textile dyes on health and ecosystem: a review of structure, causes, and potential solutions." Environ Sci Pollut Res Int. 30(4):9207-9242. doi:10.1007/s11356-022-24398-3.*

50. ^*Sudarshan S, Harikrishnan S, RathiBhuvaneswari G, Alamelu V, Aanand S, Rajasekar A, Govarthanan M (2023). "Impact of textile dyes on human health and bioremediation of textile industry effluent using microor*

ganisms: current status and future prospects." J Appl Microbiol. 134(2):lxac064. doi:10.1093/jambio/lxac064.

51. [a], [b]*Souza MCO, González N, Herrero M, Marquès M, Rovira J, Nadal M, Barbosa F, Domingo JL (2023b). "Screening of regulated aromatic amines in clothing marketed in Brazil and Spain: assessment of human health risks." Environ Res. 221:115264. doi:10.1016/j.envres.2023.115264.*
52. [a], [b]*Souza MCO, González N, Rovira J, Herrero M, Marquès M, Nadal M, Barbosa F Jr, Domingo JL (2023c). "Assessment of urinary aromatic amines in Brazilian pregnant women and association with DNA damage: influence of genetic diversity, lifestyle, and environmental and socioeconomic factors." Environ Pollut. 335:122366. doi:10.1016/j.envpol.2023.122366.*
53. [a], [b]*Nishi I, Yoshitomi T, Nakano F, Uemura H, Kawakami T (2025). "Identification of an aryl hydrocarbon receptor agonistic disperse dye in commercially available textile products by effect-directed analysis." Chemosphere. 375:144247. doi:10.1016/j.chemosphere.2025.144247.*
54. [a], [b]*Herrero M, Souza MCO, González N, Marquès M, Barbosa F, Domingo JL, Nadal M, Rovira J (2023). "Dermal exposure to bisphenols in pregnant women's and baby clothes: Risk characterization." Sci Total Environ. 878:163122. doi:10.1016/j.scitotenv.2023.163122.*
55. [a], [b]*Wang S, Lang H, Cheng J, Ma J, Wang J, Tang Z (2025). "Bisphenol compounds in female underwear manufactured in China and their potential risks to women's health." J Hazard Mater. 491:137934. doi:10.1016/j.jhazmat.2025.137934.*
56. ^*Carlsson J, Iadaresta F, Eklund J, Avagyan R, Östman C, Nilsson U (2022). "Suspect and non-target screening of chemicals in clothing textiles by reversed-phase liquid chromatography/hybrid quadrupole-Orbitrap mass spectrometry." Anal Bioanal Chem. 414(3):1403-1413. doi:10.1007/s00216-021-03766-x.*
57. ^*Carlsson J, Åström T, Östman C, Nilsson U (2023). "Solvent-free automated thermal desorption-gas chromatography/mass spectrometry for direct screening of hazardous compounds in consumer textiles." Anal Bioanal Chem. 415(19):4675-4687. doi:10.1007/s00216-023-04780-x.*
58. [a], [b]*Carlsson J, Dostberg A, Åström T, Matyjasiak J, Kallin A, Juric S, Nilsson U (2024). "Health risks from exposure to chemicals in clothing - Non-regulated halogenated aromatic compounds." Chemosphere. 363:142930. doi:10.1016/j.chemosphere.2024.142930.*
59. [a], [b]*Ji X, Liu J, Shen J, Su P, Liang J, Feng X, Liu X, Liu R (2024). "Characterization of chemical additives in daily clothing regarding human exposure and environmental emissions." Environ Sci Technol Lett. 11(6):619-625. doi:10.1021/acs.estlett.4c00297.*
60. ^*Martí M, Alonso C, Manich A, Vilder ID, Coderch L (2023). "Flame retardant textile finishing: thermal analysis and dermal security." Textile Research J. 94(1-2):69-81. doi:10.1177/00405175231199498.*

61. ^a, b^ *Åström T, Ruiz-Caldas MX, Skedung L, Chelcea I, Nilsson C, Mathew AP, Sadiktis I, Nilsson U (2024). "The fate of hazardous textile pollutants in an upcycling process for post-consumer garments." Cleaner Engin Technol. 22:100794. doi:10.1016/j.clet.2024.100794.*
62. ^ *Licina D, Morrison GC, Bekö G, Weschler CJ, Nazaroff WW (2019). "Clothing-mediated exposures to chemicals and particles." Environ Sci Technol. 53(10):5559-5575. doi:10.1021/acs.est.9b00272.*
63. ^ *Athey SN, Adams JK, Erdle LM, Jantunen LM, Helm PA, Finkelstein SA, Diamond ML (2020). "The widespread environmental footprint of indigo denim microfibers from blue jeans." Environ Sci Technol Lett. 7(11):840-847. doi:10.1021/acs.estlett.0c00498.*
64. ^ *Saleem H, Zaidi SJ (2020). "Sustainable use of nanomaterials in textiles and their environmental impact." Materials (Basel). 13(22):5134. doi:10.3390/ma13225134.*
65. ^ *Ramasamy R, Subramanian RB (2021). "Synthetic textile and microfiber pollution: a review on mitigation strategies." Environ Sci Pollut Res Int. 28(31):41596-41611. doi:10.1007/s11356-021-14763-z.*
66. ^ *Periyasamy AP (2023). "Microfiber emissions from functionalized textiles: potential threat for human health and environmental risks." Toxics. 11(5):406. doi:10.3390/toxics11050406.*
67. ^ *Lant NJ, Hayward AS, Peththawadu MMD, Sheridan KJ, Dean JR (2020). "Microfiber release from real soiled consumer laundry and the impact of fabric care products and washing conditions." PLoS One. 15(6):e0233332. doi:10.1371/journal.pone.0233332.*
68. ^ *Rashid MM, Forte Tavčer P, Tomšič B (2021). "Influence of titanium dioxide nanoparticles on human health and the environment." Nanomaterials (Basel). 11(9):2354. doi:10.3390/nano11092354.*
69. ^ *Wang M, Yang J, Zheng S, Jia L, Yong ZY, Yong EL, See HH, Li J, Lv Y, Fei X, Fang M (2023). "Unveiling the microfiber release footprint: guiding control strategies in the textile production industry." Environ Sci Technol. 57(50):21038-21049. doi:10.1021/acs.est.3c06210.*
70. ^ *Koivisto AJ, Burrueco-Subirà D, Candalija A, Vázquez-Campos S, Nicosia A, Ravegnani F, Furxhi I, Brigliadori A, Zanoni I, Blosi M, Costa A, Belosi F, Lopez de Ipiña J (2024). "Exposure assessment and risks associated with wearing silver nanoparticle-coated textiles." Open Res Eur. 4:100. doi:10.12688/openreseurope.17254.2.*
71. ^ *Svedman C, Engfeldt M, Malinauskiene L (2019). "Textile contact dermatitis: how fabrics can induce dermatitis." Current Treatment Options in Allergy. 6:103-111. doi:10.1007/s40521-019-0197-5.*
72. ^ *Sanchez Armengol E, Blanka Kerezsi A, Laffleur F (2022). "Allergies caused by textiles: control, research and future perspective in the medical field." Int Immunopharmacol. 110:109043. doi:10.1016/j.intimp.2022.109043.*

73. ^ *Linauskiene K, Zimerson E, Sörensen Ö, Antelmi A, Bruze M, Dahlin J, Malinauskiene L, Stenton J, Svedman C, Isaksson M (2022). "Patch test results to extracts of synthetic garments in textile dye positive patients." Contact Dermatitis. 87(4):325-330. doi:10.1111/cod.14182.*
74. ^ *Shirvan AR, Nouri A, Kordjazi S (2022). "Allergies caused by textiles and their control." In: Medical textiles from natural resources. Woodhead Publishing, Sawston, Cambridge, UK. 551-579. doi:10.1016/B978-0-323-90479-7.00019-1.*
75. ^ *Isaksson M, Antelmi A, Dahlin J, Stenton J, Svedman C, Zimerson E, Glas B, Hagvall L, Lagrelius M, Löwnertz A, Malinauskiene L, Matura M, Bruze M (2023). "Exclusion of disperse orange 3 is possible from the textile dye mix present in the Swedish baseline patch test series. A study by the Swedish Contact Dermatitis Research Group." Contact Dermatitis. 88(1):54-59. doi:10.1111/cod.14223.*
76. ^ *Guo Z, Cheng Y, Zhu L, Li F, Liang H, Huang Q, Wang L (2024). "Dermal Exposure to Alkylphenol Ethoxylates in As-Purchased Garments: Human Health Risk Assessment." AATCC Journal of Research. 11(6):456-463. doi:10.1177/24723444241275987.*
77. ^ *Ruiz Sánchez J, Espiñeira Sicre J, Cristóbal Redondo V, Albert Cobo I, Al-Wattar Ceballos O, Silvestre Salvador JF (2025). "Chronic prurigo associated with allergic contact dermatitis: a case series highlighting textile dyes and fragrance allergens." Contact Dermatitis. doi:10.1111/cod.14764.*
78. a, b *Kwiatkowski CF, Andrews DQ, Birnbaum LS, Bruton TA, DeWitt JC, Knappe DRU, Maffini MV, Miller MF, Pelch KE, Reade A, Soehl A, Trier X, Venier M, Wagner CC, Wang Z, Blum A (2020). "Scientific basis for managing PFAS as a chemical class." Environ Sci Technol Lett. 7(8):532-543. doi:10.1021/acs.estlett.0c00255.*

Declarations

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.