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The Health Impact of Fast Fashion: Exploring Toxic Chemicals in Clothing and Textiles

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Abstract: The fashion industry is widely recognized for its environmental challenges, but the health impacts related to textile toxicity remain significantly underexplored. Beyond the well-known issues of pollution and resource depletion, modern clothing often harbors a hidden threat: hazardous chemicals embedded within fabrics. These include dyes containing heavy metals, antimicrobial agents that foster bacterial resistance, and synthetic fibers that release microplastics. Unlike environmental discussions, the dialogue around the direct and long-term health effects of these substances is still limited. This review addresses critical yet often overlooked concerns, such as how chemicals in textiles contribute to chronic skin conditions, hormonal disruptions, and even carcinogenic risks. It also examines the proliferation of bacteria in synthetic garments, leading to dermatological infections and rapid fabric degradation. Furthermore, the globalized nature of production masks the contamination risks transferred from producer to consumer countries. Through an interdisciplinary approach, this paper highlights the urgent need for integrating scientific innovation, stringent regulation, and consumer awareness to mitigate health hazards in fashion. It calls for the adoption of safer textile technologies, sustainable materials, and transparent production practices, paving the way for a fashion future that prioritizes human health as much as environmental sustainability.

Keywords: textile toxicity; chemical pollution; health risks; sustainable fashion; antimicrobial resistance; microplastics; fast fashion; consumer safety

1. Introduction: The Invisible Threats in Fashion

The fashion industry is one of the most environmentally damaging sectors globally, contributing significantly to pollution through multiple channels, including water contamination, carbon emissions, and textile waste [1,2]. Among its most severe environmental impacts, textile production is responsible for approximately 20% of global clean water pollution due to dyeing and finishing processes [3,4] and contributes substantially to global wastewater pollution [5–7]. Additionally, the industry accounts for 35% of oceanic primary microplastics—equivalent to approximately 190,000 tonnes annually. Fashion production is also a major contributor to greenhouse gas emissions, responsible for between 8% [7,8] and 10% [7,9,10] of global CO_2 emissions. Emissions from textile manufacturing are projected to increase by 60% by 2030 [11]. Moreover, the industry generates an estimated 92 million tons of textile waste per year, a figure expected to rise to 134 million tons annually by 2030 [12]. Fast fashion production also involves extensive use of hazardous chemicals, accounting for a quarter of the world's toxic chemical consumption. For instance, dyeing just 1 kg of textile material requires an average of 449 grams of chemicals [13].

This environmental damage is directly linked to the fast fashion business model—characterized by mass-produced clothing distributed on a global scale. Modeled similarly to fast-food chains, this approach prioritizes speed and low prices, ensuring that trends move swiftly from the runway to consumers while simultaneously promoting short-term usage and disposability [14,15], with broader consequences extend beyond pollution. As a result, fast fashion not only exacerbates environmental

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harm but also perpetuates a cycle of overproduction and waste, amplifying the associated health risks of it.

Although the ecological consequences of fast fashion have been widely acknowledged by researchers [14,16–18] and recognized by international organizations such as the United Nations and the European Union [19–21], the discussions surrounding its impact on human health remain largely overlooked. Existing research on the subject remains scarce, leaving critical gaps in understanding how exposure to fast fashion products affects human health [22,23].

The highly globalized nature of the fashion industry further complicates these concerns, as its intricate supply chains span multiple continents [18]. The production of a single garment may involve cotton cultivation in China, India, or Pakistan; the production of wood-based fibers in Brazil or Russia; and the manufacturing of synthetic fibers in the U.S., Southeast Asia, or the Middle East. The process continues through yarn production in China or India, textile manufacturing in Turkey or South Korea, garment assembly in Bangladesh or Vietnam, and finally, retail distribution in Europe or the U.S. At the end of its lifecycle, the garment often reaches landfills or secondhand markets in Africa or Latin America. This long and complex supply chain makes it exceedingly difficult to track and monitor the full scope of environmental and health impacts at every stage.

The fashion industry's global supply chain is both vast and opaque, spanning multiple continents and concealing the chemical-intensive processes used in textile production. As production cycles accelerate, tracing supply chains becomes increasingly challenging, further distancing consumers from the realities of how their clothing is made. This lack of transparency benefits corporations reliant on outsourcing, impeding regulation and limiting consumer awareness of environmental damage, exploitative labor practices, and toxic chemicals present in their garments. From raw material cultivation to finished products, each stage exposes workers and consumers to harmful substances [24,25]. Addressing these hidden risks is essential, as they pose serious health and environmental consequences that demand stronger regulatory oversight and public scrutiny.

A key consequence of the fashion industry's opaque supply chains is the widespread exposure of workers to hazardous chemicals at multiple stages of production. In cotton fields, laborers regularly encounter pesticides and herbicides, often suffering from acute poisoning, chronic illnesses, and long-term environmental harm [26–28]. Factory workers who process textiles face similar dangers, handling synthetic dyes, formaldehyde, and flame retardants that can lead to respiratory issues, skin irritation, and even cancer [25,28] In garment assembly plants, finishing treatments involving phthalates and nonylphenol ethoxylates (NPEs) further expose workers to toxic substances [29,30]. These chemicals do not disappear after production; they remain embedded in the fabrics, posing ongoing health risks to consumers through skin contact [32].

Amid growing awareness of the environmental impacts of fast fashion, the equally concerning presence of hazardous chemicals in garments remains largely overlooked. The industry's globalized nature obscures these harmful processes, leaving consumers largely unaware of the toxic substances in their garments or the exploitative working conditions under which they are produced [24,25]. This lack of transparency benefits major fashion corporations, allowing them to prioritize profit over worker safety and environmental sustainability while keeping consumers disconnected from the realities of production [31].

1.1. Toxic Chemicals in the Clothing Production Chain- How Chemicals Infiltrate Our Wardrobe

Toxic chemicals permeate every stage of fabric production, from the moment a cotton seed is planted to the final touches on a garment. Although cotton crops cover only 2.4% of the world's cultivated land, they account for 6% of global pesticide use—more than any other crop [28]. In addition to pesticides, synthetic dyes and finishing agents introduce hazardous substances into textiles. Azo dyes, a class of synthetic nitrogen-based dyes, are commonly used for textile coloring, while finishing treatments often include formaldehyde, NPEs, phthalates, alkanes, benzyl benzoate, benzophenone, biphenyl compounds, butylated hydroxytoluene, and other chemicals. These substances provide assetsproperties such as wrinkle resistance and flame retardancy, while also reducing production costs—further accelerating the pace of fast fashion.

As fast fashion becomes increasingly rapid in production and distribution cycles, toxic chemicals are infiltrating wardrobes worldwide, posing risks to both consumers and garment workers. A striking example is the recent safety tests conducted by South Korean authorities in May 2024, which revealed that children's products from SHEIN contained dangerously high levels of toxic chemicals

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used to soften plastics. These included phthalates, which are known to cause hormonal disruptions, heart disease, fertility issues, and even cancer. One pair of shoes tested contained 428 times the permitted level of phthalates—the highest concentration ever recorded in the Seoul tests—while three handbags contained 153 times the legal limit. Similar safety tests of products from Timo and AliExpress showed that 43% of the 90 children's products examined, including watches, clay sets, toys, and pencils, contained hazardous substances [33,34].

This is not the first time SHEIN has been implicated in toxic product scandals. In 2022, comedian and fashion blogger Sarah Holcomb claimed in a viral video that SHEIN nail products poisoned her, resulting in an emergency room visit. The controversy gained further traction after an independent investigation by Greenpeace Germany. The study analyzed 47 items purchased from SHEIN websites across five countries (Austria, Germany, Italy, Spain, and Switzerland), including clothing and footwear for men, women, children, and infants. The results revealed that 15 of these items (32%) contained hazardous chemicals in alarming concentrations, while seven products exceeded EU regulatory limits—five of them by 100% or more [35].

Additional research has confirmed widespread contamination in fast fashion products. A 2021 investigation by CBC News, conducted in collaboration with climate chemist Miriam Diamond from the University of Toronto, tested 38 children's and adult products from SHEIN, ZAFUL, and AliExpress. The findings were concerning: one in five items contained high levels of toxic chemicals, including lead and multiple types of phthalates [36].

1.2. Environmental and Health Consequences for Global South Communities

The impact of these toxic chemicals extends beyond consumers, disproportionately affecting communities in clothing manufacturing regions, primarily in the Global South – generally economically less developed countries located primarily in Africa, Latin America, Asia, and Oceania. Many of these communities bear the brunt of environmental health hazards due to unregulated exposure to textile industry pollutants [5]. For example, in Cambodia—where the fashion industry accounted for 88% of all industrial manufacturing as of 2008—textile production was responsible for an estimated 60% of national water pollution [37].

The environmental matter of fast fashion does not end at the factory gates. Even after production, these garments continue to pose health hazards, particularly in regions where secondhand clothing accumulates in vast quantities. In West Africa and Latin America, a common practice among secondhand clothing retailers is to burn unsellable items to avoid waste disposal fees. This leads to severe air pollution, increasing the risk of respiratory and cardiovascular diseases among local populations. Burning garment waste also releases highly toxic substances, including dioxins—known carcinogens—if combustion conditions are not carefully managed [9,38].
Additionally, discarded clothing - often designated to Global South- contains hazardous chemicals such as chlorine bleach, formaldehyde, and ammonia, along with heavy metals, polyvinyl chloride (largely known as PVC), and resins used in dyeing and printing processes. The improper disposal of these textiles exacerbates environmental contamination and public health risks, reinforcing the urgent need for stricter regulations and industry accountability.

2. From Fast Fashion to Fast Toxic: The Invisible Compounds in Clothing and Textiles

The textile industry stands on multiples chemical treatments to improve fabric quality, enhance durability, and achieve specific aesthetic effects, such as formaldehyde resin treatment, used to make fabrics more wrinkle-resistant [39]. However, many of these substances do not simply disappear after manufacturing. Instead, they remain embedded in the fibers, exposing consumers to potential health risks through direct skin contact, inhalation of chemical residues, and even subsequent ingestion or inhalation of microfibers after released into the environment [40–43]. Below, we classify the major chemical groups found in clothing and textiles, along with their associated health risks.

2.1. Dyes and Pigments

The vibrant colors in modern clothing come at a cost. Many textile dyes, especially azo dyes, contain chemical components that can degrade into aromatic amines (AAs), some of which have been associated to a carcinogenic potential [29,40,44]. According to International Agency for Research on

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Cancer (IARC), certain AAs from textile have been classified as carcinogenic (Group 1 – e.g. o-Toluidine, 4-Aminobiphenyl), probable carcinogens (Group 2A – e.g. 4-Chloro-o-Toluidine) and possible carcinogens (Group 2B – e.g. 3,3-Dimethylbenzidine) [45].

In addition, heavy metals such as lead, cadmium, and mercury are frequently used to stabilize pigments and improve colorfastness [46,47]. While these elements help fabrics retain their appearance after multiple washes, they result in serious health risks. Through bioaccumulation in human body, these neurotoxic metals have been reported to cognitive impairment, kidney failure, developmental disorders in children, among other chronic health conditions [47–49].

2.2. Hydrophobic and Stain-Resistant Treatments

To make clothing water-repellent and stain-resistant, manufacturers apply coatings with per- and polyfluoroalkyl substances (PFAS). These synthetic compounds are highly persistent in the environment and human body, reason to be often referred to as "forever chemicals". PFAS have been detected in human blood, and research links prolonged exposure to immune system suppression, hormonal disruptions, damage in organs as kidney and liver, and an increased cancer risk [24,50–52]. Unlike some other chemicals that wash out over time, PFAS remain embedded in fabrics and can be released into the air or absorbed through the skin [53,54].

2.3. Conservation and Finishing

Beyond color and functionality, clothing undergoes chemical treatments to improve longevity and resistance to external factors. One of the most concerning substances used in this process is formaldehyde, which is applied to fabrics to prevent wrinkles, shrinkage, and mildew growth [39,55]. Despite its effectiveness, formaldehyde is a known carcinogen (Group 1) and can cause skin irritation, respiratory issues, and allergic reactions [45,56,57], and may be associated to brain disorders [58].

Another problematic group of chemicals in textiles is phthalates. These substances are added to synthetic materials and fabric coatings to increase flexibility, durability and anti-odor proprieties. However, phthalates are known endocrine disruptors and prolonged exposure has been associated to reproductive health issues and developmental disorders in children [59,60].

2.4. Cotton Cultivation and Synthetic Fabrics

The presence of harmful substances in clothing extends beyond the production phase—it starts at the raw material level. Conventional cotton farming relies heavily on pesticides and insecticides, which contaminate water sources and pose health risks to agricultural workers and consumers. Agricultural workers who come in contact with these products may experience acute symptoms or long-term consequences, including eye and skin irritation, neurological disorders, respiratory complications, and many other health issues [26,27]. While the direct impact of prolonged exposure to pesticide-contaminated cotton fabrics remains insufficiently studied, researches have confirmed the presence of these chemical traces in textiles. Even after processing and laundering, traces of these compounds remain persist in the fabric [26,61–63]. Otherwise, it is well established that individuals can be exposed to these substances through environmental sources [27].

Meanwhile, synthetic fabrics such as polyester and nylon present a different but equally pressing issue: microplastic pollution. With every wash, tiny plastic fibers shed from these materials and enter the water supply. Microplastics have now been detected in bloodstream samples, placental tissue, and even human lungs and brain, raising concerns about their potential genotoxic effects and their role in inflammation [42,49,64].

2.5. The Invisible Bacteria: Microorganisms in Textiles

In addition to chemical contamination, bacteria present another hidden threat in clothing. These unseen microorganisms flourish in synthetic fabrics and inadequately washed garments, creating health hazards that go beyond unpleasant odors. The interaction between bacteria and textiles, particularly in synthetic ones raises significant health and material concerns. Understanding. how bacteria proliferate in fabrics—and the consequences of their presence—is vital.

2.5.1. Bacterial Proliferation in Synthetic Fabrics and Inadequately Washed Clothing

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Synthetic fabrics, such as polyester and nylon, which are frequently used in fast and ultra-fast fashion, provide favorable conditions that encourage bacterial adhesion and growth. Their hydrophobic properties facilitate them to absorb sebum, sweat, and other organic matter, offering a steady nutrient supply for bacteria. Studies have shown that polyester fabrics exhibits a higher rate of bacterial colonization compared to cotton, primarily due to their moisture-wicking features and reduced breathability [65].

At the same time, inadequate washing practices often fail to eliminate these microorganisms effectively, allowing them to accumulate over time. Proper heat levels—ranging from 40°C to 60°C —are critical for inactivating pathogens. However, many domestic laundering routines rely on lower temperatures, typically between 30°C and 40°C. To address this, some researchers suggest incorporating bleach, such as chlorine or activated oxygen, into the washing process [66,67]. Without effective laundering, bacteria persist on garments, posing ongoing health risks. From an environmental perspective, washing clothes at lower temperatures (30°C to 40°C) is often recommended to conserve energy and extend garment lifespan. This creates a tension between energy efficiency and the need for adequate pathogen control. As a result, the use of petroleum-based synthetic fibers—already prevalent in the fast fashion industry—contributes another layer of complexity to balancing public health concerns with environmental sustainability.

2.5.2. Health Impacts: Odors, Skin Irritation, and Increased Risk of Dermatological Infections

The presence of bacteria in clothing is not merely a matter of hygiene – it's also a health risk Bacterial metabolism of sweat and organic matter produces volatile organic compounds (VOCs), leading to unpleasant odors. More critically, bacterial colonization of fabrics can cause skin irritation, allergic reactions, and an increased risk of dermatological infections, particularly in individuals with sensitive skin or compromised immune systems [68].

Pathogenic bacteria, such as *Staphylococcus aureus* and *Escherichia coli*, have been detected in clothing, raising concerns about their potential to cause infections. For instance, *S. aureus* is associated with conditions like folliculitis and impetigo, while *E. coli* can lead to urinary tract infections and gastrointestinal issues [68].

2.5.3. The Relationship Between Bacteria and Fabric Degradation: The Accelerated Life Cycle of Clothes Contaminated with Microorganisms

Beyond their impact on human health, bacterial contamination can significantly contribute to the degradation of textiles. Microorganisms secrete enzymes that break down fabric fibers, particularly in natural materials like cotton and wool. Over time, this enzymatic activity weakens the structural integrity of the fabric, resulting in pilling, discoloration, and reduced durability; These changes not only shorten the lifespan of clothing but also exacerbate the issue of textile waste, adding to environmental challenges [69].

2.5.4. Antimicrobial Treatments and Bacterial Resistance: A Double-Edged Sword

To address these concerns, manufacturers have incorporated antimicrobial treatments into fabrics, especially synthetics, with products like BioCote® serving as a prime example. These coatings either inhibit bacterial growth (biostatic effect) or kill microorganisms on contact (biocidal effect) [70]. Common additives used to achieve these effects include silver, zinc, and organic compounds [71]. However, while these treatments offer clear benefits, prolonged exposure to antimicrobial-treated textiles may foster bacterial resistance. The routine incorporation of such microbicidal agents in clothing raises concerns about their impact on skin's microbiota and the possible adverse health effects [70].

2.6. Antimicrobial Treatments: Benefits, Drawbacks, and Sustainability Challenges

Antimicrobial treatments in textiles offer several key benefits, particularly in contexts where hygiene and durability are of utmost importance. By inhibiting bacterial growth, agents such as triclosan, silver nanoparticles, and quaternary ammonium compounds help reduce microbial contamination on fabrics. This is especially valuable in environments where cleanliness is critical, such as hospitals and sports facilities [72]. Additionally, these treatments can minimize the formation

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of unpleasant odors by curbing bacterial activity, which metabolizes sweat and organic matter into VOCs [73]. Another advantage lies in extending the lifespan of fabrics: by slowing down bacterial-induced biodegradation, antimicrobial agents help preserve natural fibers like cotton and wool, potentially decreasing textile waste and supporting sustainable fashion practices [69].

However, these treatments are not without drawbacks. The widespread use of antimicrobial agents in clothing has been linked to the development of resistant bacterial strains. For example, triclosan has been shown to promote cross-resistance with antibiotics, compounding the global problem of antimicrobial resistance [74]. Similarly, silver nanoparticles, though effective against a broad spectrum of bacteria, may contribute to the emergence of silver-resistant microorganisms over time [75]. Moreover, certain antimicrobials can pose health risks. Compounds like triclosan and quaternary ammonium compounds have been associated with skin irritation, allergic reactions, and endocrine disruption [74]. The leaching of silver nanoparticles from treated fabrics further raises concerns about systemic exposure and potential long-term toxicity [76].

Environmental impacts also warrant consideration. Antimicrobial agents often leach into wastewater during laundering, where they can contaminate aquatic ecosystems and affect non-target organisms. Silver nanoparticles, for example, accumulate in water bodies, endangering aquatic life and potentially entering the human food chain [77]. Furthermore, while antimicrobial treatments may reduce bacterial growth under controlled conditions, their real-world effectiveness diminishes over time. Repeated washing, mechanical abrasion, and exposure to organic matter can undermine their efficacy [72].

As consumers become more aware of the chemicals in their clothing and the potential for bacterial proliferation, pressure is mounting on manufacturers and policymakers to adopt safer production methods. Moving toward non-toxic, sustainable textile alternatives is not only an environmental imperative but also a crucial step in protecting public health and mitigating long-term health risks.

3. From Skin to Organism: Pathways of Exposure and Health Impacts

The chemicals and microorganisms present in textiles are not confined to the fabric itself; instead, they interact with human body in ways that extend beyond simple contact. This section explores the mechanisms of exposure, and the clinical and toxicological consequences associated with these contaminants.

3.1. Dermal Absorption

The skin serves as a primary route of exposure to harmful chemicals present in textiles, including triclosan, azo dyes, phenols, and microfibers. Triclosan, an antimicrobial agent commonly used in textiles, can be absorbed through the skin and has been linked to endocrine disruption and allergic reactions [74]. Azo dyes, widely used for their vibrant colors, can degrade into mutagenic AAs upon contact with sweat or bacteria, posing risks of systemic toxicity and carcinogenicity [40]. Additionally, phenols and parabens, often found in fabric treatments, can penetrate the skin and disrupt the skin barrier, particularly in individuals with genetic predispositions, such as mutations in the filaggrin gene [43]. Microfibers, shed from synthetic fabrics, can also adhere to the skin, causing mechanical irritation and facilitating the absorption of other harmful chemicals [42].

3.2. Inhalation of Volatile Particles and Microfibers

Textiles contribute significantly to the release of VOCs in indoor environments, emitting substances such as formaldehyde, amides (e.g., N,N-dimethylformamide and formamide), and other harmful chemicals. These emissions are especially problematic in enclosed spaces, where limited ventilation can lead to the accumulation of higher concentrations of airborne toxins. Formaldehyde, frequently found in wrinkle-resistant fabrics, is both a respiratory irritant and a known carcinogen. Additionally, amides and other VOCs are associated with adverse health effects, including headaches, dizziness, and potential long-term risks [25].

In addition to VOCs, synthetic fabrics release microfibers during everyday use and laundering. These microfibers, often derived from plastics such as polyester and nylon, can become airborne and inhaled, potentially causing inflammation, oxidative stress, and even migrating to other tissues. Such exposure raises concerns about their role in respiratory diseases and systemic toxicity [32]. Moreover,

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synthetic fabrics shed microplastics into wastewater during washing. Once in the water supply, these particles can enter the food chain, exposing humans to microplastics through contaminated water and food. Inside the body, microplastics may accumulate in tissues and release toxic additives, presenting risks to gastrointestinal health and overall systemic health [32].

3.3.2. Dermatitis and Chronic Allergic Reactions

Textile-related dermatitis typically occurs at sites of intense contact with fabrics and areas prone to sweat retention, such as the axillary folds, neck, waist, inner thighs, and gluteal folds. As demonstrated in a four-year prospective study conducted in Israel, common sensitizers include not only the textile fibers themselves but also chemical agents used in dyeing and finishing processes [78]. Among these, disperse dyes, particularly Disperse Blue 106, 124, 85, and 35, are the most common allergens in clothing, while paraphenylene diamine serves as an important marker for textile-induced allergic contact dermatitis [79]. Although formaldehyde-related dermatitis has declined due to reduced formaldehyde release from fabrics, irritant reactions to textile resins and detergent residues remain significant, especially in children with atopic dermatitis. Mechanical dermatitis, caused by rough fibers or tight-fitting clothing, is also prevalent, particularly among atopics (individuals with a genetic predisposition to allergic conditions such as eczema). These findings highlight the diverse mechanisms by which textiles can trigger dermatitis, emphasizing the need for further research and awareness [78].

3.3.2. Endocrine-Disrupting Chemicals in Textiles: Mechanisms of Hormonal Disruption

Endocrine-disrupting chemicals (EDCs) present in textiles pose considerable health risks due to their ability to interfere with hormonal regulation. These persistent substances, including PFAS, phthalates, and bisphenols, can remain in the environment and accumulate within human tissues, leading to long-term health concerns. EDCs can disrupt hormonal balance through multiple mechanisms, each with distinct implications for human health.

One primary pathway is receptor binding, where EDCs either mimic or block the function of natural hormones such as estrogen, testosterone, and thyroid hormones. This interference can alter normal hormonal signaling and regulation. Another significant mechanism involves enzyme interference, whereby EDCs affect the synthesis, metabolism, or elimination of hormones, potentially disrupting the body's endocrine functions. Furthermore, some EDCs can induce epigenetic changes, modifying gene expression patterns related to hormonal pathways, with potential consequences that may extend to future generations [31].

3.3.3. Biochemical Accumulation and Long-Term Risks

Noxious substances used in textile manufacturing/treatment can progressively accumulate in the human body through repeated exposure—either directly through skin contact or indirectly after being released into the environment—leading to significant long-term health risks. One of the most concerning consequences of this process is the increased risk of cancer, as chemicals like formaldehyde and AAs from azo dyes are classified as carcinogens, with chronic exposure linked to skin, bladder, and lung cancers [45]. In addition, heavy metals such as lead and cadmium—commonly used in dyes and pigments—can accumulate within the nervous system, resulting in cognitive impairment, developmental delays in children, and, over time, neurodegenerative diseases in adults [48]. Furthermore, persistent chemicals like PFAS can build up in vital organs such as the liver and kidneys, causing long-term damage and elevating the risk of chronic health conditions [24,49,52].

4. Towards a Toxic-Free Fashion: Science-Based and Policy Solutions

The global fashion industry must adopt a multi-faceted approach that incorporates technological innovation, material development, regulatory frameworks, and consumer empowerment. By leveraging safer chemical alternatives, improving supply chain traceability, promoting sustainable fiber production, implementing robust regulatory standards, and fostering informed consumer choices, the industry can transition toward a safer, more sustainable model.

4.1. Safe and Viable Alternatives

To reduce the harmful chemicals traditionally used in textile production, manufacturers are exploring a range of innovative technologies. Natural dyes, derived from plant-based sources, offer

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an eco-friendly alternative that minimizes water pollution and lessens health risks [80]. Nanofiltration membranes effectively remove EDCs from wastewater, preventing environmental contamination [81,82]. Advanced techniques such as Right-First-Time Dyeing reduce chemical waste and energy usage by optimizing dyeing processes from the start [83]. Additionally, ozone finishing and nanobubble technology enhance textile processing efficiency while cutting down on harmful chemical use [84,85]. Together, these innovative methods offer a path forward by reducing toxicity and supporting a cleaner, safer fashion industry.

4.2. Technologies for Supply Chain Tracking

Transparency and traceability are critical to addressing chemical hazards and improving accountability across the supply chain. Digital product passports, which the European Union is actively promoting, would provide a record of a garment's chemical composition and environmental footprint, empowering both consumers and regulators. RFID and GPS systems allow real-time monitoring of raw materials, production sites, and distribution networks, making it easier to identify and address chemical hotspots [86]. Cryptographic tracking tags further enhance transparency by securely authenticating and tracing garments, preventing counterfeit products and ensuring compliance with safety standards [87]. In addition, blockchain technology is being explored to create tamper-proof records of a garment's lifecycle, ensuring transparency regarding chemical inputs and manufacturing practices. Machine learning tools can analyze production data to identify risks, while embedded sensors in manufacturing equipment monitor chemical usage and alert operators to leaks or contamination. Together, these advances improve traceability, strengthen regulatory compliance, and reduce toxic chemical exposure.

4.3. Development of Sustainable and Natural Fibers

To reduce the use of harmful substances, textile innovation is increasingly turning toward natural alternatives and bioengineered fibers that replicate the desirable properties of conventional materials without introducing toxic chemicals. PFAS substances, for example, are commonly used for their water- and stain-resistant qualities but have raised significant health and environmental concerns. Developing PFAS-free alternatives—such as plant-based coatings or naturally hydrophobic materials—can significantly lower the industry's chemical footprint. Furthermore, biodegradable fibers made from renewable sources like agricultural waste, algae, or bio-based polymers not only reduce dependency on synthetic, petroleum-derived fibers but also address issues related to end-of-life disposal. Such fibers can decompose more easily in the environment, decreasing the amount of textile waste that accumulates in landfills or waterways.

Academic research has shown that materials like polylactic acid, derived from corn starch or sugarcane, can offer comparable functionality to traditional polyester while being fully compostable under certain conditions [88]. Similarly, regenerated fibers like Tencel™ Lyocell, which is produced from sustainably sourced wood pulp in a closed-loop process, have gained traction for their low environmental impact and versatility [89]. Innovations in bioengineering are also yielding materials with enhanced performance characteristics, such as spider silk-like fibers produced by microbial fermentation, which exhibit remarkable strength and elasticity without the need for toxic additives [90].

By investing in these sustainable fiber technologies and scaling their production, the fashion industry has the opportunity to drastically reduce its environmental footprint. Consumers benefit as well, as these safer materials limit exposure to hazardous substances while providing durable, high-quality options. Transitioning to sustainable fibers not only supports healthier ecosystems but also aligns the industry with growing consumer demand for ethical and environmentally responsible fashion choices.

4.4. Urgent Regulatory Changes

Regulatory measures are pivotal in steering the fashion industry toward the elimination of toxic chemicals. The European Union's Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) regulation exemplifies this approach by mandating that companies register chemicals produced or imported in quantities exceeding one tonne per year with the European Chemicals Agency (ECHA)[91]. This process requires the identification and management of risks

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associated with these substances, thereby enhancing the protection of human health and the environment.

In the United States, the Environmental Protection Agency (EPA) enforces guidelines under the Resource Conservation and Recovery Act (RCRA), which governs the management of hazardous waste, including certain chemicals used in textile manufacturing. Compliance with these regulations is essential for minimizing environmental contamination and safeguarding public health. Drawing parallels to the U.S. government's enforcement of the Uyghur Forced Labor Prevention Act (UFLPA), which bans imports linked to forced labor from China's Xinjiang region, there is a compelling argument for implementing global legislation that addresses the importation and consumption of products containing toxic chemicals [92]. Such measures would protect consumers worldwide from exposure to hazardous substances and promote ethical production practices.

Given that policymakers may not possess specialized knowledge in textile chemistry, targeted training programs are essential to equip them with the expertise needed to effectively regulate chemical use in the industry. Educational initiatives, such as those offered by the bluesign® Academy, provide valuable insights into sustainable textile production and chemical management, thereby enhancing the capacity of regulators to make informed decisions [93].

Legislation serves as a powerful tool for public health by reducing exposure to hazardous substances. Environmental regulations have successfully mitigated pollution in various industries, demonstrating the potential for similar approaches in the fashion sector to ensure safer consumer products and a healthier environment.

4.5. The Role of Consumers and Shared Responsibility

Consumers are pivotal in driving the fashion industry toward the adoption of non-toxic and sustainable practices. Empowering individuals with transparent product labeling, accessible education, and reliable safety certifications can significantly influence purchasing behaviors, thereby fostering demand for safer garments. Transparent labeling serves as a bridge over the information gap between producers and consumers, enabling informed decisions that prioritize health and environmental sustainability. Research indicates that clear and honest labeling positively affects brand equity and consumers' purchase intentions, as long as the information is perceived to be fair and accurate [94]. Educational initiatives play a crucial role in enhancing consumer awareness regarding the environmental and health impacts of textile production. Studies have shown that increased awareness of sustainability issues leads to more responsible consumer behaviors, such as opting for eco-friendly fashion choices. Furthermore, sustainability certifications act as tools for consumers to identify products that meet specific environmental and social standards. While these certifications can bolster a brand's market position and raise sustainability awareness, they should be complemented with direct assessments and stakeholder engagement to ensure comprehensive due diligence [95,96].

Simple strategies, such as choosing clothing made from non-toxic dyes and natural fibers, can significantly reduce exposure to harmful chemicals. For instance, eco-friendly fashion emphasizes the use of materials produced with minimal chemicals, pesticides, or toxic pigments, thereby lowering the ecological footprint. This collective effort among consumers, industry stakeholders, and policymakers fosters a more accountable and health-conscious fashion ecosystem, ultimately contributing to the broader goal of environmental sustainability [97].

5. Conclusions: Decoding the Fashion of the Future

The journey toward a toxic-free fashion industry hinges on both individual choices and collective action. While consumers can drive change by making informed decisions—opting for safer materials, supporting brands committed to transparency, and demanding higher standards—systemic progress requires broader collaboration. Policymakers must enact strong regulations, the industry must embrace innovative technologies and sustainable practices, and consumers must remain vigilant in holding all stakeholders accountable. Together, these efforts can not only reduce chemical exposure and environmental harm but also pave the way for a more ethical, equitable, and sustainable future in fashion.

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One of the key lessons science offers to the textile industry is the critical need for innovation grounded in evidence. Scientific research has been pivotal in uncovering the hidden health and environmental risks associated with textile production and use, from understanding the mechanisms of chemical absorption through the skin to identifying the persistence of pollutants in ecosystems. These findings highlight the urgent need to translate scientific knowledge into practical applications, guiding the development of safer and more sustainable practices. By leveraging advances in natural dye technologies, bioengineered fibers, and non-toxic alternatives, the industry can minimize harm while driving progress toward a more responsible and forward-thinking model.

However, addressing the challenges posed by toxic chemicals in textiles requires more than isolated interventions. A holistic approach is essential—one that considers the entire lifecycle of fabrics, from production and consumer use to disposal and environmental impact. Rather than addressing each issue in isolation, stakeholders must collaborate to understand the complex interactions between chemical exposure, human health, and environmental degradation. This integrated perspective allows for more comprehensive risk management and ensures that solutions do not inadvertently create new problems.

Achieving meaningful change also demands a multifaceted strategy that encompasses research, regulation, and behavioral shifts. Continued scientific investigation is crucial to deepening our understanding of textile toxicity and identifying safer alternatives. At the same time, robust regulations are needed to phase out harmful substances and promote safer production methods. Yet, even the most stringent policies will fall short without active consumer participation. Educating the public, fostering transparency, and encouraging responsible consumption are fundamental to sustaining momentum toward change. By making informed choices and holding brands accountable, consumers can exert pressure on the fashion industry to prioritize safety and sustainability.

Ultimately, the path to a toxic-free fashion future relies on the combined efforts of scientists, policymakers, manufacturers, and consumers. By integrating scientific insight with practical innovation and regulatory commitment, we can transform the textile sector into one that values human health and environmental integrity. Only through this collective action can we envision a fashion industry that not only meets the demands of modern life but also safeguards the well-being of both people and the planet.

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